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A RAND NOTE

Performance-Oriented Logistics Assessment (POLA): Preparing the Logistics Decision Model for Use in Analyses

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RAND

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Prepared for the
United States Army

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PREFACE

This document is one of four describing the Performance-Oriented Logistics Assessment (POLA) Project. The three companion documents are:

- *Performance-Oriented Logistics Assessment (POLA): Executive Summary,* R-3823-A, which provides an executive-level overview of the POLA methodology;
- *Performance-Oriented Logistics Assessment (POLA): Users' Manual for the Logistics Decision Model (LDM), Version IV,* R-3814-A, which explains the mechanics of using the Logistics Decision Model (a PC-based theater campaign simulation model that plays a central role in the POLA methodology);
- *Performance-Oriented Logistics Assessment (POLA): Relating Logistics Functional Capacities to Resources and Costs,* N-3354-A, which discusses in some detail other parts of the methodology.

POLA was a project in the RAND Arroyo Center, sponsored by the Deputy Chief of Staff for Logistics, Directorate of Plans and Operations. Its purpose was to develop a prototype methodology to help build the logistics portion of the Army five-year program.

"Prototype methodology" describes a methodology that has been developed to the point where its usefulness has been demonstrated. That has been done: the Logistics Evaluation Agency (LEA) has adopted the prototype methodology, has built a "shell" to link the methodology with existing Army data files—such as the Total Army Equipment Distribution Program (TAEDP)—and is using the combined system on real Army logistics problems. The combined system is called Logistics Net Assessment (LNA). However, LNA is not currently a polished, user-friendly, fully supported system. Nor does it deal with all the logistics resources possible. Support of LNA and its further development (which, in the authors' opinion, would be worthwhile) are the Army's responsibility.

This is a highly technical Note that will be of particular interest to those who must prepare the Logistics Decision Model (LDM) for use in subsequent analyses. This Note depends heavily on material in the LDM User's Manual [3], which should be read before reading this Note and should be available for reference. Preparation of the LDM involves building input files for a base case. The input file that governs the combat portion of the simulation is built by calibrating the LDM so that it agrees with results from a larger, more detailed theater simulation model that is considered "correct." Then, the data files that

describe the theater support structure and support activities must be built. These tasks are discussed in this Note.

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SUMMARY

This Note explains how to prepare the Logistics Decision Model (LDM) for use in subsequent analyses. LDM was developed by the Performance-Oriented Logistics Assessment (POLA) project as part of a larger methodology. The overall POLA project is described in a companion publication [1]; it is summarized here to provide context for LDM.

THE POLA PROJECT

The POLA methodology consists of several small models, shown in Fig. S.1. LDM estimates combat performance measures (e.g., forward line of troops (FLOT) movement and attrition) from resources on hand in the theater[1] (e.g., tanks, tank crews, ammunition) and from capacities available to perform logistics functions (e.g., maintenance, ammunition distribution). Before LDM can be used for analysis, it must be calibrated and provided with a description of the theater support system (operations that are the subject of this Note). During an analysis, the user can vary the capacities and quantities of resources and observe how these variations affect combat performance measures.

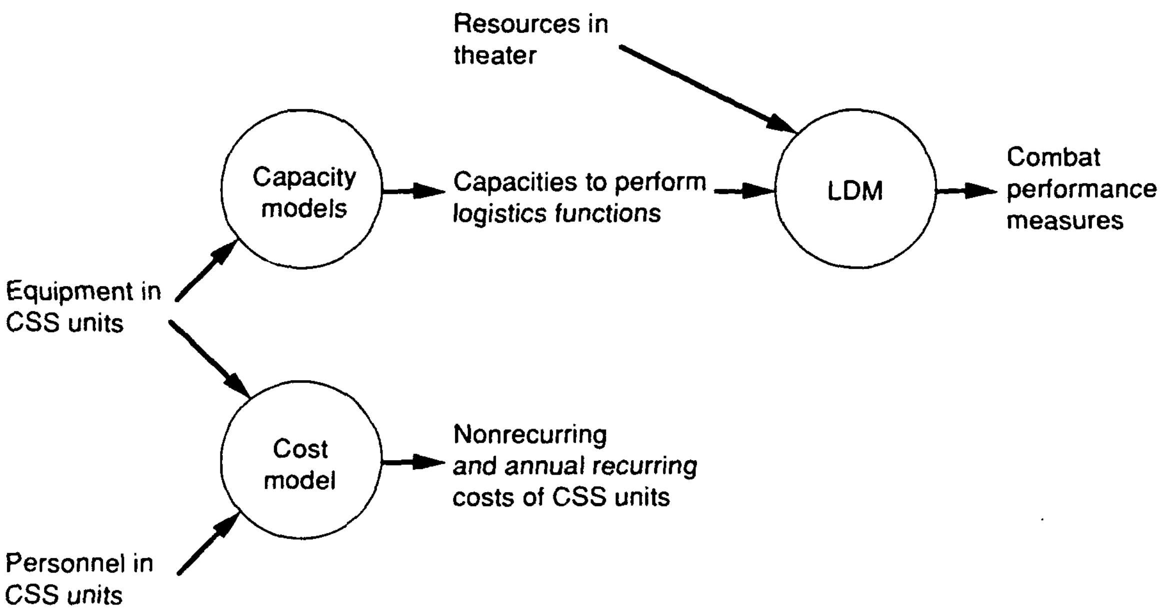

Fig. S.1— Overview of the POLA Methodology

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[1]So far, LDM has been used to simulate only the NATO theater; however, given the appropriate data, the model could be used equally well for other theaters.

Capacity models estimate the capacities needed by LDM from the equipment on hand in the Combat Service Support (CSS) units that perform logistics functions (e.g., GS (General Support) Ordnance Companies). Capacity models build on a general method borrowed from AR 220-1, "Unit Status Reporting," and tailor it to suit each specific kind of unit.

The *cost model* estimates the cost of increasing those capacities by adding or replacing equipment in those CSS units. It separately estimates nonrecurring costs (e.g., initial procurement of spares and repair parts, initial training of personnel) and annual recurring costs (e.g., replenishment of spares and repair parts, military pay and allowances, a share of depot maintenance costs). To estimate the incremental cost of improvements to CSS units, one applies the model before a unit receives a logistics improvement and then again afterwards. The cost of the improvement is the difference between the "before" and "after" cost estimates.

The methodology is particularly designed to assess logistics improvements that add capacity to perform logistics functions (e.g., ammunition distribution) to the theater support system by adding or replacing equipment in CSS units. It can also assess logistics improvements that add capacity by adding entire new CSS units, stocks of ammunition, war reserve equipment, or other resources. The methodology can also assess the effect on combat performance of reducing the capacity to perform a logistics function, although estimating the resulting savings presents problems.

A full analysis would investigate many possible logistics improvements or reductions and thus would require considering hundreds of cases. Therefore, the authors designed the methodology to be very fast (minutes per case), highly aggregated (to lessen the difficulty of preparing inputs), and very small (to fit on the PCs the Army is making readily available).

LOGISTICS NET ASSESSMENT

The U.S. Army Logistics Evaluation Agency (LEA) has adopted the methodology developed by the POLA project. The Operations Research and System Analysis (ORSA) Support Team at LEA is responsible for further developing and implementing methodology, maintaining data files, and periodically recalibrating LDM. They have created a Logistics Net Assessment (LNA) system that incorporates LDM and selected capacity models (but, as of this writing, *not* the cost model). They can provide the LNA package to action officers in the Pentagon; action officers can then perform their own mini-analyses for the resources for which they are responsible. The ORSA Support Team can also perform its own more complete analyses.

PREPARATION OF LDM FOR ANALYSIS

The task of preparing LDM for use in subsequent analyses is building a base case. The two main parts of this task are calibrating the representation of combat and preparing a representation of the theater support system.

Calibration

Calibration involves adjusting various LDM inputs so the model behaves "correctly" in a specified reference (or calibration) case. To date, the authors have calibrated LDM to cases generated by the CEM and FORCEM models. CEM (Concepts Evaluation Model) is a large theater simulation model used by the U.S. Army Concepts Analysis Agency (CAA) in a variety of studies that provide requirements information for building the Army program. FORCEM (Force Evaluation Model), a model in the late stages of development at CAA, is intended to replace CEM. Because CEM's (and FORCEM's) intended use overlaps that of the POLA methodology, the authors designed LDM to produce results consistent with those models.[2]

Huge input and output data files from either CEM or FORCEM are needed to calibrate LDM. The data can occupy several reels of magnetic tape and must be processed initially on a computer substantially larger than a PC. (The authors have used a mainframe.) The calibration process extracts from these huge files LDM inputs such as:

- Time-phased schedules for Blue and Red forces and resources to enter the theater;
- Rules governing how many of the Blue and Red forces will be engaged at different local force ratios, as a function of the overall theater force ratio;
- Rules governing how much of the force engaged at a particular local force ratio will be in each of the three engagement types ("Blue Attack-Red Defend" versus "Static" versus "Red Attack-Blue Defend");
- Attrition of each weapon system, depending on the local force ratio and type of engagement;
- FLOT movement rate, also depending on the local force ratio and type of engagement;
- And others.

[2]It should be possible to calibrate LDM to virtually any other theater model that considers only the close battle. The LDM program would have to be modified to consider deep strikes—whether against infrastructure (e.g., bridges and ports), combat units, or logistics targets. With deep strikes, the closest LDM can come is to represent their effects (e.g., decrements of resources and capacities, or delays in their addition to the theater). These effects, however, must be determined outside the model.

Calibrating LDM is an art. The authors extracted LDM inputs from the CEM or FORCEM files, then compared the results from an LDM simulation with the CEM or FORCEM outputs. Initially they do not match. So the authors must judiciously adjust the LDM inputs, being careful to maintain a reasonable relationship to the CEM or FORCEM inputs while converging toward agreement in the outputs. For example, if the inventory of Blue tanks drops lower late in the LDM simulation than at the same time in the CEM or FORCEM simulation, the authors might increase the attrition rate for Blue tanks, or reduce the fraction of damaged tanks that can be repaired. Generally, the authors must repeat the adjustment process several times.

Building the Support Structure Files

In LDM, the support structure is represented as two matrices: the *activity matrix* and the *resource matrix*. Each column of the *activity matrix* corresponds to a different support activity, such as moving ammunition from the Corps Storage Area (CSA) to the Ammunition Transfer Point (ATP), or repairing a tank at the Divisional DS Heavy Equipment Maintenance Company. Each row of the activity matrix represents a resource that can be produced, consumed, or otherwise transformed by one or more activities. Examples of resources include artillery ammunition at the CSA, tons per day of ammunition-handling capacity at the CSA, tanks in the maintenance queue at the Divisional DS (Direct Support) Heavy Equipment Maintenance Company, and maintenance man-hours per day available at the Divisional DS Heavy Equipment Maintenance Company.

Resources may be in limited supply, and LDM does not allow activities to consume more of a resource than is available. Thus, each resource corresponds to a constraint on the rates at which the support system can perform the activities that consume that resource. A resource might constrain only one activity; for example, no more artillery ammunition can be moved from the CSA to the Theater Storage Area (TSA) than is available at the CSA. Or a resource might constrain several activities simultaneously. For example, at the Divisional DS Heavy Equipment Maintenance Company, the repair of each kind of equipment is a different activity. Equipment repair of any kind expends maintenance man-hours. Because maintenance man-hours are limited, the numbers of repaired tanks plus artillery pieces plus all other kinds of equipment will also be limited. When a resource must be shared among several activities, the allocation of that resource is governed by user-specified priorities.

The *resource matrix* is used to calculate the quantity of each resource available for use during each time period of an LDM simulation. Some resources (called *stock* resources) are

carried over from the previous period, if any remain unused. For example, if any artillery ammunition remains at the CSA at the end of one time period, it is available during the next period. In addition, stock resources in transit or in process from an earlier time period may be delivered during the current period. Thus some of the artillery ammunition that began the journey from the port to the CSA in the previous time period will arrive during the current one.

Other resources (called *constraint* resources) are not carried over from previous periods. For example, maintenance man-hours not used during one period cannot be saved for future periods. Quantities of these resources in a period are calculated from available quantities of the stock resources in the same period. Thus the available maintenance man-hours in a period (a constraint resource) may be calculated from the quantity of maintenance units in the theater (a stock resource).

To build the support structure, the authors first identify various logistics functions they wish to represent, such as the distribution of ammunition or the maintenance and resupply of major items of equipment. For each logistics function, the authors must define the activities by which the function is performed. They generally lay out the function as a network, in which the links correspond to the activities and the nodes to stock resources. They also identify the constraint resources that affect the logistics function and specify the way that their available quantities are calculated for the resource matrix.

The authors define activities that place demands on each logistics function. For the ammunition distribution function, for example, they define activities that requisition ammunition from the distribution system to replace ammunition that is consumed. For the major equipment repair and resupply system, some activities generate broken items of equipment to be repaired, and other activities requisition operating equipment items to replace those lost.

Finally, the authors determine consequences for failing to meet the demands placed on the logistics function. For example, an ammunition shortage at the brigade echelon may limit the number of different kinds of weapon systems available to engage in combat. A shortage of petroleum, oil, and lubricants (POL) may limit not only the available weapon systems but also the capacity to distribute ammunition and POL itself.

For each constraint resource identified, it is necessary to specify how to calculate the amount available in each time period. For each activity, it is necessary to specify the amounts of each stock resource and constraint resource that the activity consumes or produces. This is accomplished by specifying values for coefficients in the resource matrix and activity matrix, respectively.

The authors specify many coefficients in both the resource matrix and activity matrix to be either 1.0 or –1.0. For example, the activity that moves artillery ammunition from the CSA to the ATP "consumes" 1.0 units of ammunition at the CSA and "produces" 1.0 units at the ATP. Similarly, the amount of ammunition that the Brigade echelon can requisition is 1.0 times its authorization minus 1.0 times the amount on hand minus 1.0 times the amount due in. Values for these coefficients can be obtained through logic. Other coefficient values must come from approved planning factors or Army data bases. For example, maintenance man-hours consumed per tank repaired may come from the Sample Data Collection (SDC) program. Much of the data needed to calculate transportation resources consumed by moving a unit of artillery ammunition from the CSA to the ATP can be found in Field Manual 55-15, "Transportation Reference Data."

The authors must also specify the duration for each activity. For example, maintenance activities require repair times, and transport activities require transportation times. Durations may also come from approved planning factors or Army data bases.

Once these quantities have been specified, the model is ready to be used for analyses of measures that improve logistics performance.

ACKNOWLEDGMENTS

The authors are grateful to the following people for their contributions:

- The ORSA Support Team at the Logistics Evaluation Agency (LEA) uncovered errors and suggested numerous improvements in early versions of the POLA methodology. The team has incorporated the latest versions of the models in their Logistics Net Assessment system.
- Beth Lachman of RAND reviewed this Note and made many helpful suggestions for its improvement.
- Irene Gordon prepared the manuscript for publication.

CONTENTS

FIGURES

TABLES

GLOSSARY

AEL	Aggregation Error Line
AMC	Army Materiel Command
APC	Armored Personnel Carrier
ARTY	Artillery
ASP	Ammunition Supply Point
ATM	Anti-Tank and Mortar
ATP	Ammunition Transfer Point
ATTRITION	Type of LDM input file
AWP	Awaiting Parts
BLUEATT	File created during calibration of LDM to CEM
BLUEFRAC	File created during calibration of LDM to CEM
BLUESEC	File created during calibration of LDM to CEM
CAA	Concepts Analysis Agency
CAS	Close Air Support
CEM	Concepts Evaluation Model
CEPS	Central European Pipeline System
Code H	Not repairable
COMBO	File created during calibration of LDM to FORCEM
COMMZ	Communications Zone
COSCOM	Corps Support Command
CSA	Corps Storage Area
CSS	Combat Service Support
CWR	Combat Worth Ratio
DALO-PLA	Department of the Army, Deputy Chief of Staff for Logistics, Directorate of Plans and Operations
DCSLOG	Deputy Chief of Staff for Logistics
DISCOM	Division Support Command
DS	Direct Support (*see also* GS)
EAC	Echelons Above Corps
ENGAGE	File created during calibration of LDM to CEM
ENGFRAC	File created during calibration of LDM to FORCEM
FAS	Force Accounting System

FASTALS	Force Analysis Simulation of Theater Administrative and Logistics Support
FEBA	Forward Edge of the Battle Area (same as FLOT)
F-Kill	Firepower Kill
FLOT	Forward Line of Troops (same as FEBA)
FM	Field Manual
FORCEM	Force Evaluation Model
GS	General Support (*see also* DS)
HDQTRS	File created during calibration of LDM to FORCEM
HELO	Helicopter
HET	Heavy Equipment Transporter
HNS	Host Nation Support
K-Kill	Catastrophic Kill
LDM	Logistics Decision Model
LEA	Logistics Evaluation Agency
LNA	Logistics Net Assessment
MAC	Maintenance Allocation Chart
MARC	Manpower Requirements Criteria
M-Kill	Mobility Kill
MLRS	Multiple Launch Rocket System
MMH	Maintenance Man-Hours
MOS	Military Occupational Specialty
NATO	North Atlantic Treaty Organization
ORSA	Operations Research and Systems Analysis
OUT_SPEC	Type of LDM input file
PC	Personal Computer
PM	Program Manager
POL	Petroleum, Oil, and Lubricants
POLA	Performance-Oriented Logistics Assessment
RAM	Reliability, Availability, and Maintainability
RCZ	Rear Corps Zone
REDATT	File created during calibration of LDM to CEM
REDFRAC	File created during calibration of LDM to CEM
REDSEC	File created during calibration of LDM to CEM
RHS	Right-Hand Side

SAMS	Standard Army Maintenance System
SAS	Statistical Analysis System
SDC	Sample Data Collection
SPARC	Sustainability Predictions for Army Spare Components Requirements for Combat
SRC	Standard Requirements Code
SUPCOM	Support Command
SUPPORT	Type of LDM input file
TAEDP	Total Army Equipment Distribution Program
TIME_PHASE	Type of LDM input file
TMT	Transportation Medium Truck
TOE	Table of Organization and Equipment
TRADOC	Training and Doctrine Command
TSA	Theater Storage Area
TTP	Trailer Transfer Point
UIC	Unit Identification Code
UNITSTAT	File created during calibration of LDM to FORCEM
USBLUEAT	File created during calibration of LDM to CEM
USENGAGE	File created during calibration of LDM to CEM
USREDATT	File created during calibration of LDM to CEM

1. INTRODUCTION

This Note explains how to prepare the Logistics Decision Model (LDM) for use in subsequent analyses. This Note depends heavily on the LDM Users' Manual [3], which should be read first. LDM was developed by the Performance-Oriented Logistics Assessment (POLA) project as part of a larger methodology. The POLA project is described in a companion publication [1]; to provide context for LDM, it is summarized in the following paragraphs.

THE POLA PROJECT

Performance-Oriented Logistics Assessment, a project sponsored by the Army DCSLOG, Directorate of Plans and Operations (DALO-PLA), has developed a prototype methodology to help build the logistics portion of the Army five-year program. When building its program, the Army first estimates a requirement for each resource, but the price of satisfying all requirements always greatly exceeds the amount the Army can spend. Therefore, the Army prioritizes the different requirements; it decides which ones will be funded immediately and which ones will be deferred, perhaps for several years. The Army has always made these decisions on somewhat arbitrary grounds, because it has never developed tools that would systematically rate different resources, intended to support disparate functions, on common scales.

The POLA methodology attempts to rectify this lack by estimating the impact on combat performance of alternative investments in logistics resources. Combat performance measures thus become the common scale on which different resources are rated. If an increment of one resource has relatively little impact on combat performance and an equal-cost increment of a second resource has a large impact, the Army may prefer to satisfy less of the requirement for the first resource and more of the requirement for the second.

Combat performance is measured in terms of FLOT (Forward Line of Troops) movement, Red and Blue weapons engaged and attrited, and Red and Blue resources consumed and personnel lost. Logistics resources include stocks of ammunition; petroleum, oil, and lubricants (POL); war reserve equipment; and replacement personnel. Also considered are resources that increase Combat Service Support (CSS) capacities, such as capacities to handle ammunition, transport dry cargo, and so on.

THE POLA METHODOLOGY

The POLA methodology consists of several small models, as shown in Fig. 1.1. The LDM is intended to estimate the effects of logistics improvements on combat performance. It simulates the ways that Red and Blue combat forces are influenced by CSS capacities (e.g., transportation, ammunition handling, maintenance) and by logistics resources (e.g., stocks of ammunition, war reserve equipment, replacement personnel).

Figure 1.2 shows LDM inputs and outputs. The user represents logistics modifications as changes in capacities or available resources from a base case. By comparing a logistics modification case with the base case, he can estimate the effects of the logistics changes on combat performance measures. The user can also observe indicators of logistics "health," such as maintenance queues, vehicles abandoned for lack of recovery assets, excess capacities, and so on.

By itself, LDM cannot do all that is required of the POLA methodology. It can estimate the effect on combat performance of varying the capacities to perform certain logistics functions, such as ammunition or POL handling. But those capacities must themselves be estimated from physical resources. For example, the handling capacity of a DS (Direct Support) Ordnance Company must be estimated from the numbers of its fork lifts

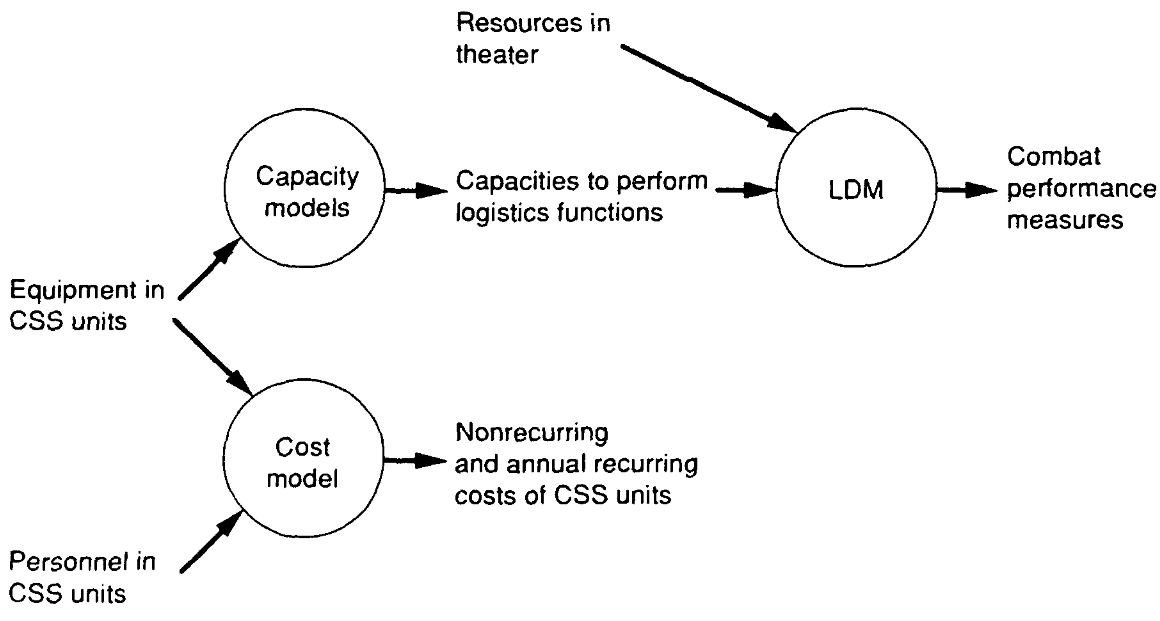

Fig. 1.1— Overview of the POLA Methodology

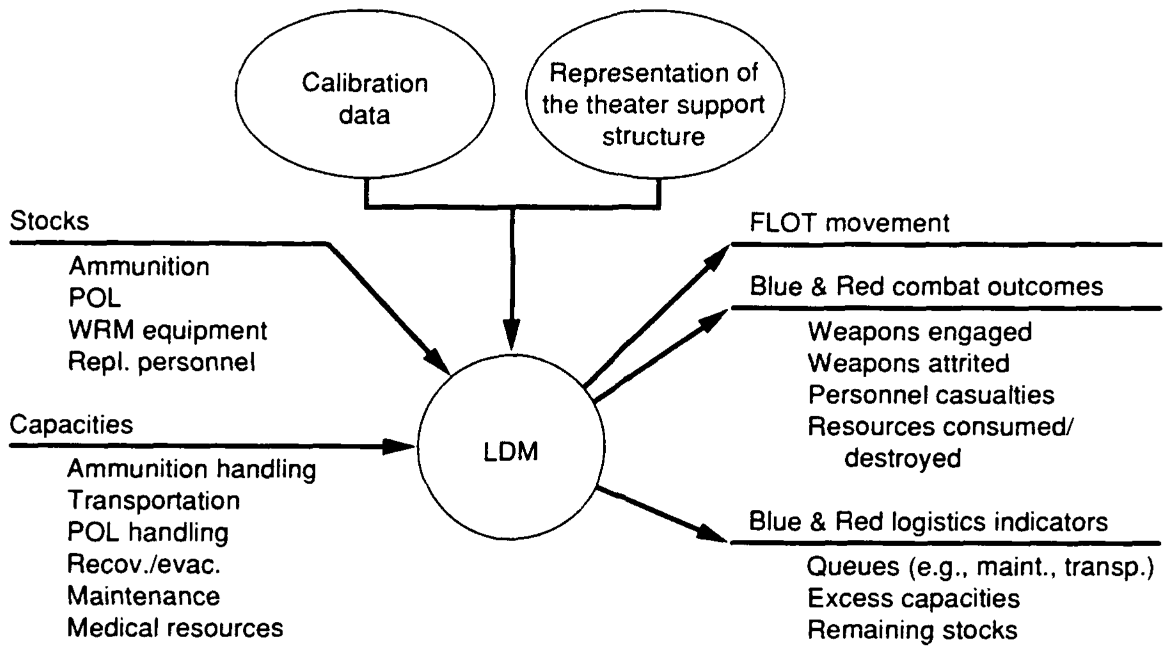

Fig. 1.2—LDM Inputs and Outputs

and cranes, and their operators. In the POLA methodology, this is done by capacity models (see Fig. 1.1).

One must further estimate the dollar costs of these resources. The cost-estimating procedures must estimate much more than the current purchase price of a particular resource. Buying a resource (e.g., a variable-reach forklift) commits the Army to a number of other expenditures as well (e.g., expenditures for training crews and maintenance personnel, fuel, storage facilities). The procedures must estimate the overall cost of equipping and fielding a new unit, or they can be applied to incremental resources to estimate the cost of adding resources and/or people to an existing unit. Cost estimation is performed by a cost model (see Fig. 1.1). Both the cost model and the capacity models are described in [2].

It is also necessary to build a base case and several logistics improvement cases for LDM. The base case should reflect the Army programmed for the analysis year (the current year, or a specified future year). Logistics improvement cases are best defined as modest changes from the units and resources the Army possesses in the base case. In [2], we have identified Army data bases that describe the current Army and the Army that is currently programmed for the future, and we have worked out procedures for drawing from these data bases the unit and resource data we need.

LOGISTICS NET ASSESSMENT

The U.S. Army Logistics Evaluation Agency (LEA) has adopted the methodology developed by the POLA project. The ORSA Support Team at LEA is responsible for further developing and maintaining the methodology, for maintaining data files, and for periodically recalibrating LDM and providing it to action officers in the Pentagon. The ORSA Support Team has created a *Logistics Net Assessment* (LNA) system that consists of:

- An input processor, written as a dBase III application;
- The LDM program;
- An output analyzer, in the form of Lotus 1-2-3 spreadsheets with macros; and
- A graph generator, which uses Lotus Graph Writer.

These modules are integrated through the use of DOS batch files. Users interested in obtaining the entire LNA system should contact the ORSA Support Team at LEA.

PREPARATION OF LDM FOR ANALYSIS

The task of preparing LDM for use in subsequent analyses is building the LDM input files for a base case. LDM reads four kinds of input files: the ATTRITION file, one or more SUPPORT files, one or more OUT_SPEC files, and the TIME_PHASE file.[1] These files are described in detail in the LDM Users' Manual [3], which should be read before attempting to read this Note.

The LDM model consists of a combat module and a support module. The combat module uses mostly data from the ATTRITION and TIME_PHASE files, and some data from the SUPPORT files, to calculate combat results such as FLOT movement, attrition of weapon systems, and losses and consumption of resources. Calibration involves establishing the combat module inputs so the model reproduces the combat results from a specified reference (or calibration) case.

To date, we have calibrated LDM to cases generated by the CEM and FORCEM models. CEM (Concepts Evaluation Model) is a large theater combat simulation model used by the U.S. Army Concepts Analysis Agency (CAA) in a variety of studies that provide requirements information for building the Army program. FORCEM (Force Evaluation Model), a model in the late stages of development at CAA, is intended to replace CEM.[2]

[1] In this Note, we discuss how to build the ATTRITION, SUPPORT, and TIME_PHASE files, but not how to build the OUT_SPEC files. The OUT_SPEC files merely tell LDM what quantities to write to the various output files. They do not affect LDM's calculations. See [3], Chapter 6.

[2] CEM and FORCEM are similar in many ways. Both simulate a theater campaign in which 50 to 100 Blue brigades face a similar number of Red divisions. Their simulations proceed by 12-hour time

To exercise either model, CAA must invest months of effort preparing and tuning the input data, and interpreting the results. Running either model requires a mainframe computer. Because CEM's (and FORCEM's) intended use overlaps that of the POLA methodology, we designed LDM to produce combat results consistent with those models.[3]

LDM's support module uses the remaining data from the SUPPORT files to simulate logistics functions such as resupply of ammunition and POL, and repair and resupply of equipment. Because FORCEM simulates some of these functions, its inputs and outputs can be used to establish some of the remaining SUPPORT data. However, the user may wish to add logistics functions not in FORCEM or to represent functions differently. If so, the SUPPORT data must be obtained from other sources. CEM contains only the most rudimentary representations of logistics functions, and its inputs and outputs can hardly be used to establish SUPPORT data.

To build the support structure description, we first identify the various logistics functions we wish to represent. For each logistics function, we must define the activities by which the function is performed. We generally lay out the function as a network, in which the links correspond to transportation activities and the nodes to other kinds of activities (e.g., storage and handling of ammunition, or repair of equipment). Each activity is defined in terms of the resources it affects (e.g., a repair activity "consumes" a broken tank and "produces" an operable one). We also identify constraints that affect the logistics functions, such as transportation or maintenance capacities. These constraints can affect several activities simultaneously.

We also define activities that place demands on each logistics function, and we provide consequences for failing to meet the demands placed on the logistics function. For example, for the ammunition distribution function, we define activities that requisition ammunition from the distribution system to replace the ammunition that is consumed. If the ammunition is not replaced, the resulting ammunition shortage at the BRIGADE echelon may limit the numbers of different kinds of weapon systems available to engage in combat.

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steps. When combat occurs between a Blue and Red unit, its outcome is decided in the same way for both models, based on the number of up to 51 different kinds of weapons that each unit possesses. The models differ in that FORCEM treats movement of units more flexibly than CEM, and it contains more elaborate representations of logistics functions.

[3]It should be possible to calibrate LDM to virtually any other theater model that considers only close battle. The LDM program would have to be modified to consider deep strikes—whether against infrastructure (e.g., bridges and ports), combat units, or logistics targets. With deep strikes, the closest LDM can come is to represent their effects (e.g., decrements of resources and capacities, or delays in their addition to the theater). These effects, however, must be determined outside the model.

ORGANIZATION OF THIS NOTE

Sections 2 and 3 explain how LDM can be calibrated to combat results from FORCEM and CEM, respectively. Sections 4 through 7 show, through several examples, how a user can formulate a desired support structure for an LDM simulation. One support structure is distributed with the LDM program as part of a test case. Section 4 presents several ways to improve on the representation of weapon systems found in the test case. Sections 5, 6, and 7 present formulations of ammunition distribution, bulk POL (petroleum, oil, and lubricants) distribution, and maintenance, respectively, that differ from the formulations of these functions in the test case. Appendixes A and B discuss the mathematical formulation combat and support, respectively, in LDM. Appendix C discusses details of LDM's implementation as a computer program.

2. CALIBRATING LDM TO A FORCEM CASE

This section is the first of two that deal with calibrating LDM. By calibration, we mean establishing values for the data in the ATTRITION and TIME_PHASE files, as well as a few coefficients in the SUPPORT files, so that combat results from LDM match those generated by other models, in particular CEM and FORCEM. That is, we have adjusted ATTRITION, TIME_PHASE, and some SUPPORT data so that LDM's results agree with the results from either a CEM or FORCEM case. In this section, we discuss how we calibrated LDM to FORCEM results. In the next section, we will discuss calibrating LDM to CEM results.[1]

FORCEM INPUT AND OUTPUT DATA FILES NEEDED

The FORCEM model has not yet been completely developed. Among other things, its output files have been changing. Old output files have been modified to include additional data elements, and new output options have been created. Also, no publications describing FORCEM or its input and output files have been released. (CAA has generously provided unpublished draft descriptions of the files and parts of the model.) The user who attempts to calibrate LDM to a new FORCEM case must be aware that the process described in this section will most likely have to be modified to account for changes in FORCEM since late 1987, the last time we calibrated to a FORCEM case.

Table 2.1 shows the input and output files used the last time we calibrated LDM to a FORCEM case. These files come from CAA on magnetic tape, coded as either ASCII or EBCDIC characters. The total size of these files exceeds 80 megabytes, too large to process conveniently on a PC. A workstation or mainframe computer is recommended for processing these files.

Aggregation

The LDM simulation is much less detailed than the one performed by FORCEM. First, FORCEM keeps track of many individual Blue and Red units (divisions, plus higher headquarters), whereas LDM lumps all forces at a given echelon into a single pool. (As configured for the test case, LDM considers the same four echelons as FORCEM—namely, BRIGADE, DISCOM, COSCOM, and THEATER.)

[1]Clearly, there are other models to which LDM might be calibrated. Also, one might build the ATTRITION and SUPPORT files entirely from planning factors and historical data, and the TIME_PHASE file from deployment plans, and not calibrate LDM to a detailed theater-level model at all.

Table 2.1

FORCEM Input and Output Files Needed

Input Files	Output Files
Asset Data	Report 26, Engagements
Resupply Data	Report 28, Combat HQ Status
Logistics Data	Report 29, Personnel-Ammo-POL
	Report 30, Weapons On Hand #1–12
	Report 31, Weapons On Hand #13–24
	Report 32, Weapons On Hand #25–29
	Report 38, CSS SUPCOM
	Report 40, CSS Convoy Flow
	Report 44, Weapons On Hand #30–41
	Report 45, Weapons On Hand #42–51
	Report 49, Division Personnel Assets
	Report 50, Division Supply Assets
	Report 51, Division Equipment Assets
	Report 53, Equipment Pool
	Report 54, Personnel Pool
	Report 64, Loss & Consumption
	Debug 39, Effective Weapons

Second, FORCEM considers five different engagement types. In LDM, they are aggregated into three postures, shown in Table 2.2.

Finally, FORCEM considers hundreds of asset types, including up to 51 different weapons. LDM must aggregate these into a smaller number. There is little choice in how LDM aggregates the FORCEM weapons because many output reports, including ones needed to estimate the attrition functions (Reports 49–51), give information for groups of weapons rather than individual weapons. Which of the 51 weapons belongs to each group has been changed from time to time. In the test case, weapons were grouped as shown in Table 2.3.

(In the most recent FORCEM case we examined, this grouping had been changed. There were still seven groups, each of which we made to correspond to one LDM weapon. However, the FORCEM weapons in each group were somewhat different, as shown in Table 2.4.)

Table 2.2

FORCEM Engagement Types Versus LDM Postures

FORCEM Engagement Type	LDM Posture
1. Blue Attack, Red Defend	Blue Attack
2. Blue Attack, Red Delay	Blue Attack
3. Red Attack, Blue Defend	Red Attack
4. Red Attack, Blue Delay	Red Attack
5. Static	Static

Table 2.3

Aggregation of Weapons for the Test Case

FORCEM Weapon	Group	
1–12	TANK	
13–24	APC	(Armored Personnel Carrier)
25–29	HELO	(Helicopter)
30–41	ATM	(Anti-Tank and Mortar)
42	INFANTRY	
43–50	ARTY	(Artillery)
51	CAS	(Close Air Support)

Table 2.4

Aggregation of Weapons in a Recent FORCEM Case

FORCEM Weapon	Group	
1–6	TANK	
7–24	APC	(Armored Personnel Carrier)
25–29	HELO	(Helicopter)
30–41	ATM	(Anti-Tank and Mortar)
42	INFANTRY	
43–50	ARTY	(Artillery)
51	CAS	(Close Air Support)

Assets other than weapons are also aggregated in some reports. The user must look at the FORCEM asset file, and decide how to aggregate the asset types based on the needs of the analysis.

Preparatory Processing

We use SAS (Statistical Analysis System)[2] to carry out the data analysis and file manipulations involved in calibrating LDM to FORCEM. As the first step in calibration, we merge some of the FORCEM output reports into a smaller number of files. We also create some files used in more than one of the calibration tasks. Figure 2.1 shows which FORCEM files contribute data to the files generated during preprocessing.

[2]SAS (Statistical Analysis System) is a trademark of the SAS Institute, Inc. Although SAS is rich in statistical procedures, we have not used them much in the calibration process. Mostly, we used operations such as merging and partitioning files; sorting, summarizing, and tabulating data; and performing simple calculations.

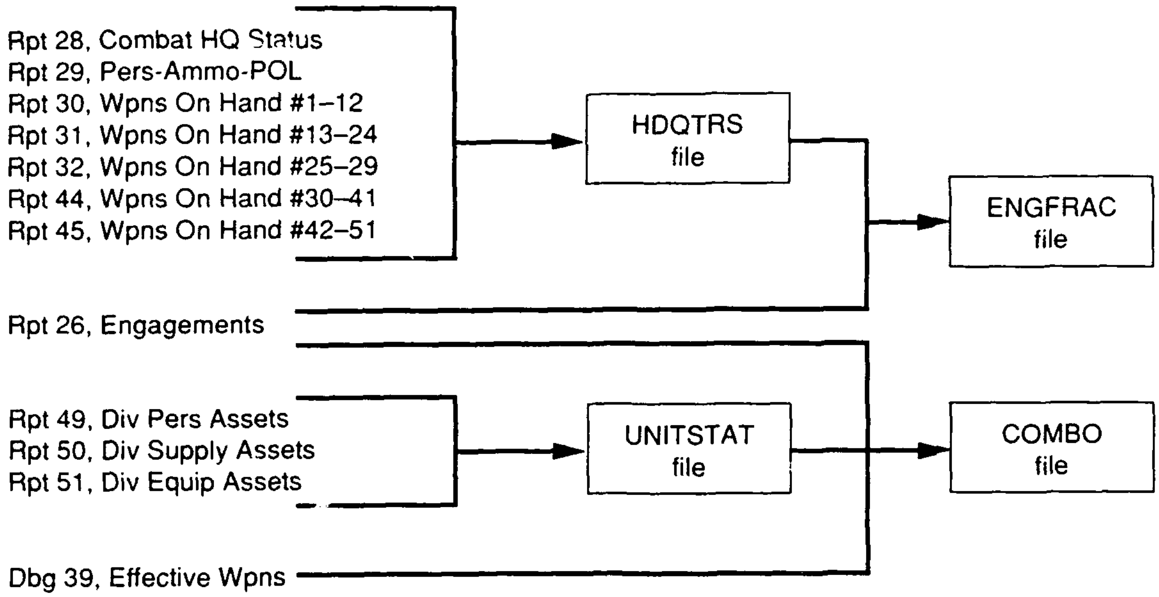

Fig. 2.1—Data Flows in Preprocessing of FORCEM Files

The HDQTRS File

Seven of the output reports that FORCEM produces—Reports 28–32, 44, and 45—are in essence seven parts of the same report; we merge them into a single file called HDQTRS.

The merge operation matches records from each of these files that have the same combinations of time, unit, and side, and combines them into a single record in the HDQTRS file. Units are divisions or higher headquarters (Corps, Army, and Theater). Sides are Blue or Red.

The HDQTRS file contains one record for each Blue or Red unit in each simulation cycle that finds that unit in the theater. Each record includes the data elements shown in Table 2.5. In contrast to some FORCEM reports, there are individual equipment inventories for all 51 types of weapons considered in FORCEM.

The ENGFRAC File

We calibrate LDM only to the U.S. portion of the FORCEM simulation. We do so because LDM is intended to examine the effect of improving U.S. logistics support on combat performance. The combat performance measures would be diluted if we included a large part of the theater that U.S. logistics resources did not help support.

The ENGFRAC file contains data elements to partition the theater into U.S. and non-U.S. portions. For each division (Blue and Red) in each simulation cycle that finds it in the

Table 2.5

Data Elements in the HDQTRS File

Time (=simulation cycle)
Unit ID (divisions and higher headquarters)
Side (Blue or Red)
Nationality (U.S., non-U.S. Blue, or Red)
Echelon
Engagement status (yes or no)
Location (XY coordinates)

Inventories at the start of the simulation cycle of:

Weapon crews	Tank ammunition	Tanks (weapons 1–12)
Combat personnel	Artillery ammunition	APCs (weapons 13–24)
Helo crews	Special ammunition	Helos (weapons 25–29)
Other personnel	Other ammunition	ATMs (weapons 30–41)
	POL	Infantry (weapon 42)
		Artillery (weapons 43–50)
		CAS (weapon 51)

theater, ENGFRAC contains fractions of units assigned to, and engaged in, the U.S. portion of the theater in each simulation cycle. We call these the *unit fraction assigned* (UFA) and *unit fraction engaged* (UFE), respectively.

The ENGFRAC file is built from the HDQTRS file and Report 26, the engagements report. The data elements in the HDQTRS file are shown in Table 2.5. Table 2.6 shows the most important elements in Report 26. For any division at any time, Report 26 may have several records, or no records. If there are no records, the division is not engaged. If there are records, some may identify a U.S. division as the Blue unit, and others may not. The fraction of a division that is engaged in the U.S. part of the theater at a particular time is the fraction of that division's combat worth that can be found in records of that time whose Blue unit is a U.S. division. (The HDQTRS file will contain a record for each division in any cycle that finds it in the theater, whether or not it is engaged. The fact that the division is in the theater is the only information needed from the HDQTRS file.)

Table 2.6

Data Elements in Report 26, Engagements

Time (=simulation cycle)
Engagement type
IDs of Blue and Red units in this engagement
Blue and Red combat worths engaged
Percent of the Blue and Red units' total combat worths engaged

For a U.S. division, the UFA in any simulation cycle is zero if the division has not yet entered the theater; it becomes one once the unit has entered the theater. The UFE can be found in the HDQTRS file. A U.S. division has a UFE of zero in a cycle if its engagement status in that cycle is "No" (see Table 2.5); otherwise, it is one. No intermediate fractions occur in the FORCEM cases we have dealt with; if any part of a unit is engaged, all of it is engaged.

For a Red division, determining the assigned and engaged fractions is more difficult, because we wish to determine when the unit, or part of it, is assigned or engaged in the U.S. portion of the theater. We are not merely interested in when it enters or engages in any part of the theater. For each Red division "i" in each cycle "t" we define three fractions:

$F1_{it}$ = fraction of Red division "i" engaged with U.S. divisions in cycle "t"

$F2_{it}$ = fraction of Red division "i" engaged with non-U.S. divisions in cycle "t"

$F3_{it}$ = fraction of Red division "i" not engaged in cycle "t"

If, according to the HDQTRS file, the division has an engagement status of "No," we set $F3_{it} = 1$ and $F1_{it} = F2_{it} = 0$. Otherwise, $F1_{it}$ is the fraction of the division's combat worth engaged with U.S. divisions (from Report 26; see Table 2.6). Similarly, $F2_{it}$ is the fraction of the division's combat worth engaged with non-U.S. divisions. And $F3_{it} = 1 - F1_{it} - F2_{it}$.

The UFE of the Red division is just the fraction engaged with U.S. divisions, or:

$$UFE_{it} = F1_{it} \tag{2.1}$$

The UFA is more difficult to assign. Logically, the fraction assigned to the U.S. portion of the theater cannot be less than the fraction engaged there, nor can it be larger than the fraction not engaged outside the U.S. portion of the theater. That is:

$$F1_{it} \le UFA_{it} \le 1 - F2_{it} \tag{2.2}$$

where UFA_{it} is the fraction of Red division "i" assigned to the U.S. portion of the theater in simulation cycle "t." In each cycle, the selected value of UFA is arbitrary, so long as it is in this range. In the first cycle, we set UFA to the fraction of the division engaged in the U.S. portion of the theater. In later cycles, we choose UFA so it will change as little as possible. This rule is embodied in the following expressions:

$$UFA_{i1} = UFE_{i1} \tag{2.3a}$$

$$UFA_{it} = \mathrm{Min}\{\ \mathrm{Max}\{\ UFA_{i,t-1}, F1_{it}\ \}, (1-F2_{it})\ \}\quad (\text{for } t > 1) \tag{2.3b}$$

(In the FORCEM cases we have examined, whenever any part of a division was engaged, all of it was engaged. That is, either $F3_{it} = 0$ or $F3_{it} = 1$. This makes possible some minor simplifications.)

Finally, we construct the change in the unit fraction assigned (DUFA) from one cycle to the next. This quantity will be used in calculating the rate of entry into the theater of resources owned by units. This quantity is:

$$DUFA_{i1} = UFA_{i1} \qquad (\text{first simulation cycle}) \tag{2.4a}$$

$$DUFA_{it} = UFA_{it} - UFA_{i,t-1} \qquad (\text{all later cycles}) \tag{2.4b}$$

Table 2.7 shows the data elements in the ENGFRAC file. As a reminder, the assigned and engaged fractions are the fractions assigned to and engaged in the U.S. portion of the theater.

The UNITSTAT File

Three output reports produced by FORCEM, Reports 49–51, are essentially three parts of the same report; we merge them all into a single file called UNITSTAT. The merge operation matches records from these files that have the same combinations of time, unit, "partition," and "Flag," and combines them into a single record in the UNITSTAT file. The "partition" code distinguishes the side a unit belongs to and, for Blue units, whether the unit is U.S. or non-U.S. The "Flag" code specifies the point in the simulation cycle at which the data in the record were collected.

"Flag" takes on the values 1 to 5, which correspond to the following points in the cycle:

Table 2.7

Data Elements in the ENGFRAC File

Time
Side
Unit ID
Unit fraction engaged (UFE)
Unit fraction assigned (UFA)
Change in unit fraction assigned (DUFA)

FLAG=1. Beginning of the cycle;

FLAG=2. After GS artillery strikes (this is deep interdiction by artillery; the effect of artillery used during an engagement is accounted for in the later "combat and movement" stage);

FLAG=3. After air strikes (this is deep interdiction by air; the effect of close air support in an engagement is accounted for in the later "combat and movement" stage);

FLAG=4. After combat and movement (includes the effects of artillery used during the engagement and the effects of close air support);

FLAG=5. After CSS (end of cycle—same as beginning of next cycle).

The UNITSTAT file contains five records for each Blue or Red division (no records for higher headquarters) for each simulation cycle that finds the unit in the theater. The five records correspond to the five points in the cycle distinguished previously. The data in each record include the elements shown in Table 2.8. Many of the data elements are the same as those in the HDQTRS file, but there are some new kinds of personnel and supplies. Also, the 51 FORCEM weapon types are summarized to six of the groups in Table 2.3 or 2.4, whereas the HDQTRS file contains separate inventories for each of the 51 FORCEM weapon types. However, the HDQTRS file gives data at only the start of each simulation cycle, whereas the UNITSTAT file gives its data at five points in the cycle.

Table 2.8

Data Elements in the UNITSTAT File

Time (=simulation cycle)
Unit ID (divisions only)
Partition
Flag

Resource inventories, authorized and on hand:

Weapon crew	Tank ammunition	Tanks
Combat personnel	Artillery ammunition	APCs
Helo crew	Special ammunition	Helos
Support personnel	Other ammunition	ATMs
Other personnel	POL	Artillery
Artillery personnel	Repair parts	Close Air Support
	Other supplies	

The COMBO File

The COMBO file is created from the UNITSTAT file, Report 26, and the Debug 39 file. The primary purpose of the COMBO file is to support later development of the attrition functions, but it also supports development of coefficients for certain CBT_LOSS functions, and it provides data with which to compare results from the (eventually) calibrated LDM.

From UNITSTAT we take inventories of all resources for Flag=3, and the differences between inventories from Flag=3 to Flag=4. These differences are the amounts of the resources that are lost or consumed in combat. From the Debug 39 report, we take the numbers of each weapon in each division at each time period that are engaged. (The fact that the division is engaged does not mean that all of its weapons are engaged. For example, some may not be engaged because of lack of crews.) These must be aggregated from the 51 weapon types considered in FORCEM, into the groups that correspond to LDM weapons (see Table 2.3 or 2.4).

Finally, we assign each division in each time period to one of the three LDM postures, and to one of the sixteen combat worth ratio (CWR) categories (see Table 2.9). These assignments are based on data in Report 26, the engagement report. Some divisions have one part engaged in one posture, and another part engaged in another posture. These divisions are coded as having posture "M" for "mixed." The COMBO file has the data elements shown in Table 2.9.

DEVELOPING DATA FOR THE ATTRITION FILE

The ATTRITION file contains six different kinds of data (see [3], Chapter 4). Only four kinds of data are obtained by manipulating FORCEM input and output data. These four are posture functions, combat worth coefficients, attrition functions, and combat loss coefficients. The other two kinds of data in the ATTRITION file—the specification of combat worth ratio categories and the FLOT movement functions—require no data analysis. Figure 2.2 shows the files used to construct these ATTRITION data.

To understand the sections that follow, it is helpful to have a listing of ATT.DAT, the ATTRITION file for the test case. This is one of the files on the floppy disks distributed with the LDM Users' Manual [3].

CWR Categories Data

These data specify the categories into which LDM will partition combat worth ratios (i.e., the CWR categories). They should be left as they are in Appendix A, Table A.1.

Table 2.9

Data Elements in the COMBO File

Time (=simulation cycle)		
Unit ID (divisions only)		
Partition		
LDM Posture		
CWR Category		
Inventories of resources on hand at Flag=3 (before the "combat and movement" stage):		
Weapon crew	Tank ammunition	Tanks
Combat personnel	Artillery ammunition	APCs
Helo crew	Special ammunition	Helos
Support personnel	Other ammunition	ATMs
Other personnel	POL	Artillery
Artillery personnel	Repair parts	Close Air Support
	Other supplies	
Losses of resources from Flag=3 to Flag=4 (during "combat and movement" stage):		
Weapon crew	Tank ammunition	Tanks
Combat personnel	Artillery ammunition	APCs
Helo crew	Special ammunition	Helos
Support personnel	Other ammunition	ATMs
Other personnel	POL	Artillery
Artillery personnel	Repair parts	Close Air Support
	Other supplies	
Inventories of engaged weapons:		
Tanks	Helos	Artillery
APCs	ATMs	Close Air Support
	Infantry	

Posture Data

The posture functions are generated from data in Report 26. We drop engagements for which the Blue unit is not a U.S. unit. Next, we compute the ratio of Blue to Red combat worths in the remaining engagements and assign each engagement to a CWR category and a posture, based on the FORCEM engagement type (Table 2.2). Finally, we create a two-way table, whose rows and columns correspond to CWR categories and LDM postures, respectively. Each cell in the table contains the sum of combat worth (Red plus Blue) in all the engagements that have the appropriate posture and combat worth ratio category.

Each cell also contains the fraction of the row total that the entry represents. These fractions form the posture data that appear in the ATTRITION file. They can be used as is, or plotted for each posture separately as a function of combat worth ratio and then smoothed.

	Posture data	Cbt worth coeffs	Attrition tables	CBT loss coeffs
FORCEM inputs				
Asset data	•	X	•	•
Resupply data	•	•	•	•
Logistics data	•	•	•	X
FORCEM reports				
Rpt 26, Engagements	X	•	•	•
Rpt 38, CSS SUPCOM	•	•	•	•
Rpt 40, CSS Convoy Flow	•	•	•	•
Rpt 53, Equipment Pool	•	•	•	•
Rpt 54, Personnel Pool	•	•	•	•
Rpt 64, Loss & Consumption	•	•	•	X
Preprocessed files				
HDQTRS file	•	X	•	•
ENGFRAC file	•	•	•	•
UNITSTAT file	•	•	•	•
COMBO file	•	•	X	X

Fig. 2.2—FORCEM Data Sources for the LDM ATTRITION File

Figure 2.3 shows the POSTURE functions used in the test case. One can think of them as probabilities that forces opposing each other at a given combat worth ratio will fight in that posture. Note that the posture functions are not symmetric with respect to side. Red is more likely to attack at a given Red-to-Blue ratio than Blue is to attack at the corresponding Blue-to-Red ratio.

FLOT Movement

FORCEM estimates the movement of a division in combat using the functions shown in Table 2.10.[3] These functions relate movement to the ratio of the attacker's to the defender's combat worth [4]. We assume that this approximates FLOT movement. However, we are aware that divisions move for reasons other than combat. (For example, a division might fall back if its neighbor retreats, even though it faces weak opposition.) We are also aware that these other movements will affect the position of the FLOT. Figure 2.4 shows graphs of the functions shown in Table 2.10.

[3]The rationale for these functions is not known to the authors.

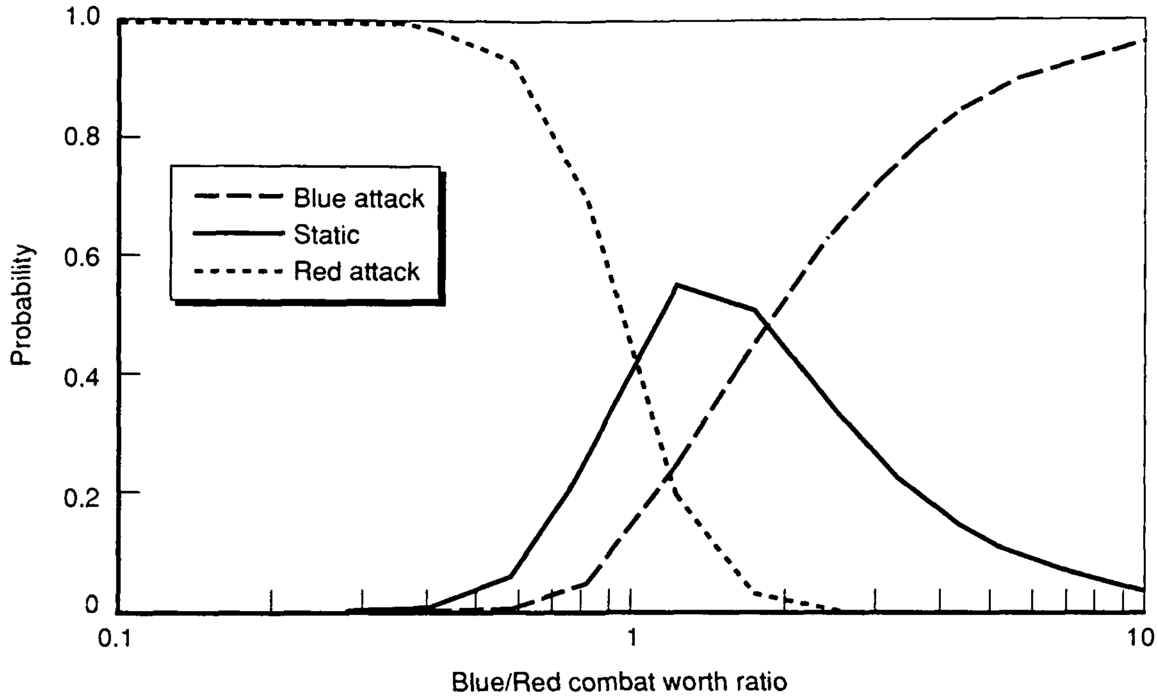

Fig. 2.3—Probabilities of the Different Engagement Types

The Combat Worth Coefficients

The combat worth coefficients are calculated for each LDM weapon on each side. Two kinds of input are required for these calculations: global importance numbers for each of the 51 weapon types considered in FORCEM (in the asset data); and inventories of the 51 weapon types (in the HDQTRS file).

Table 2.3 (or 2.4) shows how the 51 FORCEM weapons might be grouped into LDM weapons. We simply form weighted averages of the global importances of the weapons in a group, using the theaterwide inventories of those weapons as the weights. If the relative number of weapons in the group changes over time, the combat worth coefficient will also change. However, the relative numbers do not change very much in the FORCEM cases that we have seen.

Attrition Data

As described in Appendix A, LDM estimates the number of weapon systems hit by opposing fire by means of a table-lookup procedure. For each kind of weapon system, there is one "hit rate" table for Blue weapons and another for Red. Each table contains 3×16 entries,

Table 2.10

FLOT MOVEMENT FUNCTIONS

Movement in Blue Attack-Red Defend Engagements

$$\text{Blue Mvt} = \begin{cases} \dfrac{-23.3637}{1 + \exp(3.978 - 1.0426 \times \mathrm{RCW/BCW})} & \text{if RCW} > \text{BCW} \\ \dfrac{23.3637}{1 + \exp(3.978 - 1.0426 \times \mathrm{BCW/RCW})} & \text{if RCW} < \text{BCW} \end{cases}$$

$$\text{Red Mvt} = \begin{cases} 0 & \text{if RCW} > \text{BCW} \\ \dfrac{-21.4286}{1 + \exp(3.978 - 1.0426 \times \mathrm{BCW/RCW})} & \text{if RCW} < \text{BCW} \end{cases}$$

Movement in Static Engagements

Blue Mvt = Red Mvt = 0

Movement in Red Attack-Blue Defend Engagements

$$\text{Blue Mvt} = \begin{cases} \dfrac{-23.3637}{1 + \exp(3.978 - 1.0426 \times \mathrm{RCW/BCW})} & \text{if RCW} > \text{BCW} \\ 0 & \text{if RCW} < \text{BCW} \end{cases}$$

$$\text{Red Mvt} = \begin{cases} \dfrac{21.4286}{1 + \exp(3.978 - 1.0426 \times \mathrm{RCW/BCW})} & \text{if RCW} > \text{BCW} \\ \dfrac{-21.4286}{1 + \exp(3.978 - 1.0426 \times \mathrm{BCW/RCW})} & \text{if RCW} < \text{BCW} \end{cases}$$

for each of 3 postures and 16 CWR categories. Each entry specifies the fraction of engaged weapon systems of that type that will be hit in one 12-hour simulated time period.

The data needed for this exercise are inventories of weapons engaged and weapons hit in various combinations of posture and CWR category. These data were collected in the COMBO file (described previously). We sum the inventories of engaged and hit weapons of each type over all records with the same posture and CWR category, and calculate the ratio of hits to engaged weapons. These ratios can be used directly as the attrition functions, or they can be plotted as functions of CWR and smoothed. (The next section discusses a possible adjustment to the attrition functions.)

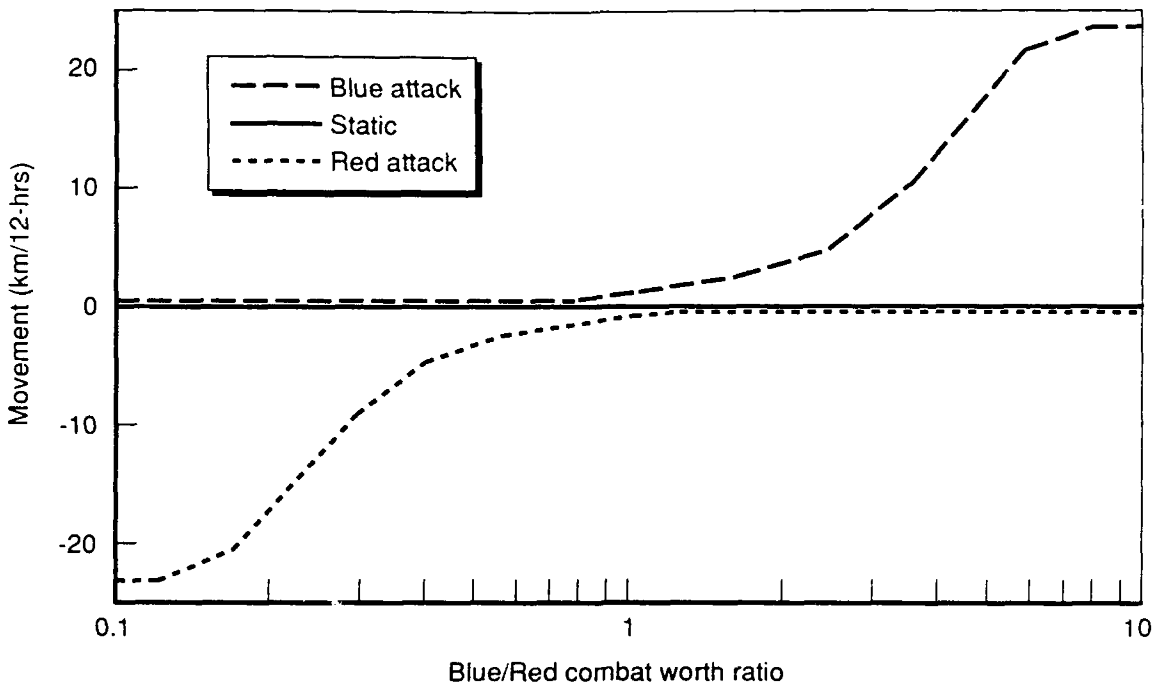

Fig. 2.4—FLOT Movement by Engagement Category

An extra step is required to obtain the attrition functions for infantry. For each of the other weapon systems, there is an equipment resource unique to that weapon system, so that each hit on the weapon system is "marked" by the loss of one of that kind of equipment in the combat and movement stage of the FORCEM simulation. However, the "infantry" weapon system is composed of one "combat personnel" and one unit of "other ammunition." Both of these resources occur in other weapon systems, so neither serves as a marker for hits on infantry.

The ATM weapon system is the only other weapon system besides infantry of which combat personnel are a part. Combat personnel can be lost, therefore, only as ATM crews or as infantry. Each record in the COMBO file contains a number of combat personnel lost that we must apportion between these two kinds of losses. That is:

$$\text{(Total combat personnel lost)} = \text{(Combat personnel lost as ATM crews)}$$
$$+ \text{(Combat personnel lost as Infantry)}$$

We assume that the number of combat personnel hit as members of ATM crews is proportional to the number of ATMs hit. That is, there is some factor α such that:

$$(\text{Combat personnel lost as ATM crews}) = \alpha \times (\text{ATMs lost})$$

Looking over all records in the COMBO file, we determine for each side the largest value that its factor α can take without the combat personnel lost as ATM crews exceeding total combat personnel lost.

$$\alpha = \text{Min}\left\{\frac{\text{Total combat personnel lost}}{\text{ATMs lost}}\right\}$$

where the minimum is taken over all records in the COMBO file.

To obtain the number of infantrymen hit, we subtract ATM crew losses (estimated as proportional to ATM hits) from the total combat personnel losses. That is:

$$\begin{aligned}(\text{Combat personnel lost as Infantry}) &= (\text{Total combat personnel lost}) \\ &\quad - \alpha \times (\text{ATMs lost})\end{aligned}$$

This calculation is carried out on each record of the COMBO file for Blue and Red separately. Then, in the same way as for the other weapon systems, we use the ratios of these losses to engaged infantry (or smoothed versions of these ratios) to describe the attrition function for infantry.

A potential problem with this approach is that the losses of equipment items in the COMBO file include not only hits on weapons but also equipment abandoned because of insufficient recovery or evacuation assets. In the FORCEM cases we have examined, there have always been ample recovery and evacuation assets, so this has not been a problem. But the user should check for abandoned equipment in any new FORCEM case to which he wishes to calibrate LDM. Report 63, the FORCEM recovery and evacuation report, may provide data that can be used not only to check whether equipment has been abandoned but also to partition the losses in the COMBO file into hits and abandonments.

Combat Loss Coefficients

As described in [3], Chapter 4, LDM estimates quantities of resources consumed in engagements by means of linear functions of the numbers of weapon systems engaged and hit during battle. Sources for these coefficients are the COMBO file, Report 64 (Loss and Consumption), and Logistics Data (a FORCEM input file).

Equipment. For each type of combat equipment, there are three combat loss functions: one each to calculate catastrophic kills (K-Kill), firepower kills (F-Kill), and

mobility kills (M-Kill). In these combat loss functions, engaged weapons all have coefficients of zero, so it is necessary only to estimate the coefficients of weapons hit.

The coefficients are obtained from Report 64 and the Logistics Data file. Report 64 contains several categories of theaterwide losses of every asset for each simulation cycle, as shown in Table 2.11. To obtain the combat loss coefficients, we first add the losses in Report 64 for all assets in each of the groups of assets that correspond to the LDM weapons (see Table 2.3 or 2.4). For any group—i.e., any LDM weapon—the fraction of hits that are K-Kills is the fraction of total combat losses that are permanent. That is, the coefficient of hits in a K-Kill combat loss function is the following ratio:

$$KK = \frac{PERM}{PERM + TEMP} \tag{2.5a}$$

where PERM and TEMP are the permanent and temporary combat losses calculated from Report 64 for the LDM weapon. Although in principle this ratio may change from one simulation cycle to the next, it appears to be quite stable in the FORCEM runs we have examined. Thus we calculate the ratio using the total permanent and temporary combat losses for all cycles of the simulation.

To obtain the F-Kill and M-Kill coefficients, we look to the Logistics Data file. Among these data are two arrays of interest: the firepower kill array and the fix forward array. Each of these arrays has two rows, one each for Blue and Red. Each column in the arrays corresponds to a FORCEM "vehicle class."[4] The fix forward array contains the fractions of

Table 2.11

Data Elements in Report 64, Loss and Consumption

Time (=simulation cycle)
Partition (U.S. Blue, non-U.S. Blue, and Red)
Asset number
Amount authorized
Amount on-hand
Amount in repair (for equipment) or in hospital (for personnel)
Amount permanently lost in combat this cycle
Amount temporarily lost in combat this cycle
Amount permanently lost not in combat this cycle
Amount temporarily lost not in combat this cycle
Amount fixed forward (included in temporary losses)

[4]The assignment of vehicles to vehicle classes has changed from one FORCEEM simulation to another. If the reader ever wishes to calibrate LDM to another FORCEM case, he must ask CAA what assignment applies. We arranged the LDM weapons to correspond pretty closely with the vehicle classes in the FORCEM cases we used for calibration.

FORCEM's temporary losses of the various vehicle types that can be returned directly to combat, without a delay for recovery, evacuation, or repair. Of those vehicles that are not fixed forward, the firepower kill array contains the fractions that suffer firepower kills, and can therefore recover themselves. Temporary losses that are not fixed forward and are not firepower kills are mobility kills; they require a recovery vehicle to be recovered. Let "f" and "x" denote the appropriate entries from the firepower kill and fix forward arrays, respectively, the coefficients of weapons hit in F-Kill and M-Kill combat loss functions are:

$$FK = \frac{(1 - x) \times f \times TEMP}{PERM + TEMP} \tag{2.5b}$$

$$MK = \frac{(1 - x) \times (1 - f) \times TEMP}{PERM + TEMP} \tag{2.5c}$$

Equipment that is fixed forward is returned directly to the equipment inventory in the division. If it is returned at Flag=4, the end of the combat and movement phase of the simulation cycle, it will have reduced the losses calculated in COMBO and should not be reflected again in the K-Kill, F-Kill, and M-Kill combat loss coefficients. One may adjust for this by dividing either the attrition table or each of the coefficients KK, FK, and MK by the sum KK + FK + MK.

In practice, it may not be very important to adjust for equipment fixed forward. In the FORCEM cases we have seen, the fractions of equipment that are fixed forward are small—in fact, often zero. In any case, the equipment fixed forward might not be returned to the division until Flag=5, after the CSS phase of the cycle. In this case, one should leave the attrition functions and combat loss coefficients as described previously.

Personnel. There are two combat loss functions for each type of personnel that enters combat: one for those permanently lost and one for those evacuated from the battlefield in need of medical care. Because a single personnel type can serve as crew for more than one weapon, each of these functions may have coefficients of several weapons.

The coefficients are obtained in two steps. First, we regress the total number of each personnel type lost against the numbers of weapons lost of which that personnel type is crew. These data can be found in the COMBO file, where there is a data point for each division in each simulation cycle. The regression coefficients are estimates of the numbers of each personnel type lost plus wounded per hit on each vehicle.

Second, we split each regression coefficient into two parts: one for permanent losses and one for casualties needing medical care. We used the split between permanent and temporary losses shown for the theater as a whole, calculated from Report 64.

Ammunition. Coefficients for the consumption of the three ammunition types can be estimated by regressing the ammunition consumed against weapons engaged and hit. The necessary data are in the COMBO file, where each division provides one data point in each simulated cycle.

DEVELOPING DATA FOR THE SUPPORT FILES

Most of the coefficients in the SUPPORT files (see [3], Chapter 5) are obtained from structural considerations (i.e., the forms of the networks for various aspects of logistics support), or from planning factors. However, some SUPPORT coefficients can be obtained from FORCEM input and output data. In the test case, the coefficients obtained from FORCEM data were as follows: the coefficients in the READY activities (activities that combine resources into weapon systems ready to engage); the fractions of hit weapons that require DS repair or GS repair, or that are beyond repair (i.e., Code H); the number of maintenance man-hours required per repair, for each type of combat equipment; and average times for transportation activities. Figure 2.5 shows which files are used to build these SUPPORT data.

Coefficients for the READY Activities

The coefficients in the READY activities[5] specify how many crew members and how much ammunition are necessary to field a weapon of each type. These coefficients are calculated in much the same way as the combat worth coefficients. The asset data (a FORCEM input file) contain the size of the crew and the amounts of each kind of ammunition needed for each of the 51 FORCEM weapon types. For each LDM weapon, we form a weighted average of these coefficients, where the weights are the inventories of the FORCEM weapons found in the HDQTRS file. The average is taken over all FORCEM weapons in the group that corresponds to the LDM weapon.

DS Repair, GS Repair, and Code H Fractions

The fractions of hit weapons that require DS repair or GS repair or that are beyond repair (i.e., Code H) come directly from the Logistics Data (a FORCEM input file). They

[5]See the file BATTLE.DAT, one of the SUPPORT files for the test case that is distributed with the LDM program. The other test case SUPPORT files are MAINT.DAT and PERSUP.DAT. They are discussed in [3].

	READY activities	Repair fractions	Mnt man-hrs per repair	Transp. times
FORCEM inputs				
Asset data	X	•	•	•
Resupply data	•	•	•	•
Logistics data	•	X	X	•
FORCEM reports				
Rpt 26, Engagements	•	•	•	•
Rpt 38, CSS SUPCOM	•	•	•	•
Rpt 40, CSS Convoy Flow	•	•	•	X
Rpt 53, Equipment Pool	•	•	•	•
Rpt 54, Personnel Pool	•	•	•	•
Rpt 64, Loss & Consumption	•	•	•	•
Preprocessed files				
HDQTRS file	X	•	•	•
ENGFRAC file	•	•	•	•
UNITSTAT file	•	•	•	•
COMBO file	•	•	•	•

Fig. 2.5—FORCEM Data Sources for the LDM SUPPORT Files

appear in two arrays: the Direct Support array and the Code H array. Each of the arrays has two rows, for Blue and Red respectively, and a column for each "vehicle class" (see footnote 4). The coefficients from the Direct Support array are placed in the TO .. NEED DS records following the EVACUATE activities for the various weapons.[6] The coefficients from the Code H array go in the TO .. CODE H records. The coefficients in the TO .. NEED GS records are calculated as one minus the sum of the NEED DS and CODE H coefficients.

Maintenance Man-Hours per Repair

The maintenance man-hours required to repair each weapon also come directly from the Logistics Data, from the Maintenance Hours array. This array has four rows, corresponding to Blue DS, Blue GS, Red DS, and Red GS maintenance man-hour requirements, respectively. Once again, the columns are FORCEM vehicle classes. These coefficients are placed in the MMH .. REPAIR records following the DS REPR and GS REPR activities for all the echelons at which repair occurs.[7]

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[6]See the BATTLE.DAT file.

[7]See the MAINT.DAT file.

The maintenance man-hour requirements need some interpretation. Typically, one thinks of maintenance personnel (and other support personnel) as spending their time in one of three ways. Some of their time represents direct labor hours (for example, the actual time spent changing a turret on a tank). Another fraction of their time represents indirect labor hours (for example, time spent cleaning and calibrating tools). The remainder of their time represents overhead or nonproductive time (for example, time spent eating and sleeping). The coefficients from the FORCEM Maintenance Hours array may include only direct labor hours, or the sum of direct labor plus a pro rata share of indirect labor hours, or (least likely) direct labor plus a pro rata share of both of the other categories. Depending on which categories are included, one must calculate the available maintenance man-hours (i.e., the right-hand sides of the MMH .. REPAIR constraints) differently.

Transportation Times

Transportation times for resupply activities can be estimated from Report 40, the CSS Convoy Flow report. In FORCEM, all resupply occurs via convoys, which may travel by truck, rail, or barge. Report 40 contains two or more records for each convoy, one record for each event involving that convoy—including its start from its origin, its arrival at its destination, and any air or artillery strikes it suffers along the way. Each record contains the data elements shown in Table 2.12.

In FORCEM, convoys can travel from the theater (or port) to the COSCOM (Corps Support Command), or from COSCOM to DISCOM (Division Support Command). One can

Table 2.12

Data Elements in Report 40, CSS Convoy Flow

Time (=simulation cycle)	
Origin unit ID	
Destination unit ID	
Mode (truck, rail, or barge)	
Side (Blue or Red)	
Convoy ID	
Start time	
Destination flag (1=on the road, 2=arrived at destination)	
Inventories of resources carried:	
Weapon crew	Tank ammunition
Combat personnel	Artillery ammunition
Helo crew	Special ammunition
Support personnel	Other ammunition
Other personnel	POL
Artillery personnel	Repair parts
	Other supplies

determine which echelons serve as the origin and destination of a convoy by looking at the origin and destination unit IDs. The travel time of a convoy can be determined by finding the latest record with a given convoy ID, and subtracting the start time from the time of that record. In the test case, we used the average time for all convoys traveling between a given pair of echelons as the duration of all the resupply activities between those echelons. We used the same times for the DS EVAC and GS EVAC activities.[8]

Durations of Other Activities

We found no data in the FORCEM inputs or outputs that could be used to estimate the durations of the repair activities. In the test case, we assumed that repairs were accomplished by teams of four people; so the duration of the repair activity was the number of maintenance man-hours divided by four.

Similarly, we found no FORCEM data from which to estimate the time wounded personnel spent in the hospital. We set the numbers used for the test case arbitrarily long enough that few wounded returned to duty within the 10 days that were simulated.

DEVELOPING DATA FOR THE TIME_PHASE FILE

The LDM TIME_PHASE file (see [3], Chapter 7) contains three sorts of data. The TIME records contain the Blue and Red fractions of available weapon systems that are engaged in each simulation cycle, as well as the standard deviations of the combat worth ratio (CWR) distribution. The other records in the TIME_PHASE file contain resource quantities that enter the theater at each cycle. Figure 2.6 shows which files are used to generate the TIME_PHASE data. It is helpful to have available the TIME_PHASE file for the test case, NOMTIME.DAT, as you read this section. Like all data files for the test case, it is on the floppy disks distributed with the LDM Users' Manual [3].

Engaged Fractions

These input parameters specify the fractions of available Blue and Red forces that engage at each simulation cycle. We estimate these fractions from the COMBO and ENGFRAC files. From the COMBO file, we take the on-hand weapon inventories for all divisions at each simulation cycle. From the ENGFRAC file, we take the fractions of each division that are currently engaged in, and assigned to, the U.S. portion of the theater. Then we apply the following equation:

$$\text{Engaged Fraction} = \Sigma[UFE_{it}W_{kit}]/\Sigma[UFA_{it}W_{kit}] \quad (2.6)$$

---
[8] See the BATTLE.DAT file.

	Engagement fractions	Standard deviations	Unit resources at brigade	Other unit resources	Theater resupply
FORCEM inputs					
Asset data	•	•	•	•	•
Resupply data	•	•	•	•	X
Logistics data	•	•	•	•	•
FORCEM reports					
Rpt 26, Engagements	•	X	•	•	•
Rpt 38, CSS SUPCOM	•	•	•	X	•
Rpt 40, CSS Convoy Flow	•	•	•	•	•
Rpt 53, Equipment Pool	•	•	•	X	•
Rpt 54, Personnel Pool	•	•	•	X	•
Rpt 64, Loss & Consumption	•	•	•	•	•
Preprocessed files					
HDQTRS file	•	•	X	•	•
ENGFRAC file	X	•	X	X	•
UNITSTAT file	•	•	X	•	•
COMBO file	X	•	•	•	•

Fig. 2.6—FORCEM Data Sources for the LDM TIME_PHASE File

where UFE_{it} and UFA_{it} are the fractions of units engaged in and assigned to the U.S. portion of the theater, and W_{kit} is the inventory of weapon "k" in unit "i" at cycle "t." The summations are taken over all units "i" at a particular cycle "t." The same equation can be used for either Blue or Red.

Standard Deviation of the Combat Worth Ratio Distribution

We use data from Report 26 to estimate the standard deviation of the log-normal distribution of combat worth ratios in each cycle (see Appendix A). The standard deviation governs the extent to which the local combat worth ratios between engaged Blue and Red forces will deviate from the theaterwide average ratio. A higher standard deviation means that a larger fraction of the Blue and Red forces will be engaged at combat worth ratios much larger and much smaller than the theater average. A lower standard deviation means that more of the Blue and Red forces will be engaged at combat worth ratios close to the theater average.

We calculate two sample means and two sample standard deviations of the logarithms of the combat worth ratios of the engagements in each cycle, using standard formulas from

statistics. There are *two* sample means and standard deviations in each cycle—not one—because one can calculate the mean and standard deviation with respect to the Blue or the Red engaged combat worth.

If the combat worth ratio distributions of Blue and Red combat worth were both log-normal, the two standard deviations would be identical, and the two means would be related according to Equations A.4a and A.4b in Appendix A. Unfortunately, this is not the case. We have devised a number of schemes to calculate a compromise value for the standard deviation, but the average of the two values calculated above is probably as good as any.

Quantities of Resources Entering the Theater

It should be possible to develop inventories of resources entering the theater during each simulation cycle by using FORCEM input files. However, we elected to use mostly data from output reports. One reason for this is that the input data are harder to split between the U.S. and non-U.S. portions of the theater. Another reason is that divisions take some time after they enter the theater to arrive at the BRIGADE echelon where they can engage; it is difficult to estimate this delay time from the input data alone.

Resources in Units at BRIGADE. We estimate quantities of resources entering at the BRIGADE echelon from the ENGFRAC, UNITSTAT, and HDQTRS files. The resources entering at this echelon are owned by divisions that are initially deployed, or that later deploy, into the U.S. portion of the theater. The following formula applies.

$$DELQ_{rt} = \Sigma[DUFA_{it}\ Q_{rit}] \tag{2.7}$$

where Q_{rit} is the quantity of resource "r" in unit "i" at cycle "t," from the UNITSTAT or HDQTRS file, and $DELQ_{rt}$ is the total amount of resource "r" in units or fractions of units newly assigned to the U.S. portion of the theater in cycle "t." $DUFA_{it}$ was defined earlier [Equations (2.4a) and (2.4b)] as the change in the unit fraction assigned (UFA_{it}) from one time period to the next.

Resources in Units at DISCOM, COSCOM, and THEATER. We estimate resources entering at the DISCOM and COSCOM, and some resources entering at the THEATER echelon, by using the ENGFRAC file and FORCEM Reports 38, 53, and 54. These resources belong to units that begin the simulation at these echelons or that deploy later. The contents of these three reports are shown in Tables 2.13 to 2.15. When the SUPCOM, eauipment pool, or personnel pool is attached to a division (i.e., is at the DISCOM echelon), one can identify the division to which it is attached from the SUPCOM ID or Pool

Table 2.13

Data Elements in Report 38, CSS SUPCOM

Time (=simulation cycle)	
SUPCOM ID	
Resource inventories on hand:	
Driver personnel	Tank ammunition
Recovery personnel	Artillery ammunition
Supply personnel	Special ammunition
Medical personnel	Other ammunition
Maintenance personnel	POL
	Repair parts
	Other supplies

Table 2.14

Data Elements in Report 53, Equipment Pool

Time (=simulation cycle)		
Pool ID		
Resource inventories, authorized and on hand:		
Tanks	ATMs	Close Air Support
APCs	Infantry weapons	Trucks
Helos	Artillery	Recovery vehicles

Table 2.15

Data Elements in Report 54, Personnel Pool

Time (=simulation cycle)	
Pool ID	
Resource inventories, authorized and on hand:	
Weapon crew	Support personnel
Combat personnel	Other personnel
Helo crew	Artillery personnel

ID. For these units, it is possible to obtain from ENGFRAC the appropriate fractions of their resources that enter the U.S. portion of the theater in each cycle.

For Blue units at higher echelons (i.e., COSCOM or THEATER), it is possible to tell from the unit ID whether the unit is U.S. or non-U.S. We have included 100 percent of U.S. unit resources at the first simulation cycle the unit appears in the relevant FORCEM report,

and we have entirely excluded non-U.S. Blue unit resources. We have not developed a satisfactory way to split Red unit resources between the U.S. and non-U.S. portions of the theater when the unit belongs to a higher echelon, so we have arbitrarily assigned 100 percent to the U.S. portion. For Blue and Red units at higher echelons, we do not include changes in resources that occur in cycles after the cycle in which the unit first appeared in the theater. These later changes are due to transactions within the theater—receipts from, or issues to, other units—and are not due to additions from outside the theater.

Resupply of Resources to the THEATER Echelon. Finally, we estimate other resources entering at the THEATER echelon using the resupply data (a FORCEM input file). These resources do not belong to any unit, but rather are used to replace losses that units suffer in the course of the simulation. These data are given by asset number and must be aggregated into the groups of assets that correspond to LDM resources. Splitting assets between the U.S. and non-U.S. portions of the theater is a straightforward process for Blue assets; in the FORCEM cases we have examined, these assets are identified explicitly as being U.S. or non-U.S. However, Red assets are not split in this way. We have not found a satisfactory way to split them, and so we have arbitrarily made 100 percent of the Red resupply assets available to the Red units in the U.S. portion of the theater.

Smoothing. It is not a good idea to remove a resource from the theater by including a negative quantity of that resource in the TIME_PHASE data. To avoid this, we smooth the data as shown in Fig. 2.7. For each resource at each echelon, we calculate a cumulative quantity of resource added at each cycle. If this cumulative quantity monotonically increases over time, we leave it alone. Otherwise, we construct a new cumulative curve that remains constant over any range in which the original curve dips downward. The new curve rejoins the old curve when the old curve regains the value at which it started down.

Finally, we deaccumulate the new cumulative curve. We take the value of the curve at the initial simulation cycle to be the quantity of the resource that enters the theater at the start of the simulation. The amount that enters in any other cycle "n" is the difference between the value of the curve at cycle "n" and the value at cycle "n – 1."

Adjusting Recovery and Evacuation Assets. In all the FORCEM cases we have examined, the recovery and evacuation constraints have been disabled. This means that no equipment items are abandoned on the battlefield. If the reader is calibrating LDM to a new FORCEM case, he should ask CAA whether recovery and evacuation constraints are still disabled. If so, he may create a similar effect in LDM by adding large numbers of recovery vehicles and HETs (Heavy Equipment Transporters) at the BRIGADE echelon. This may be

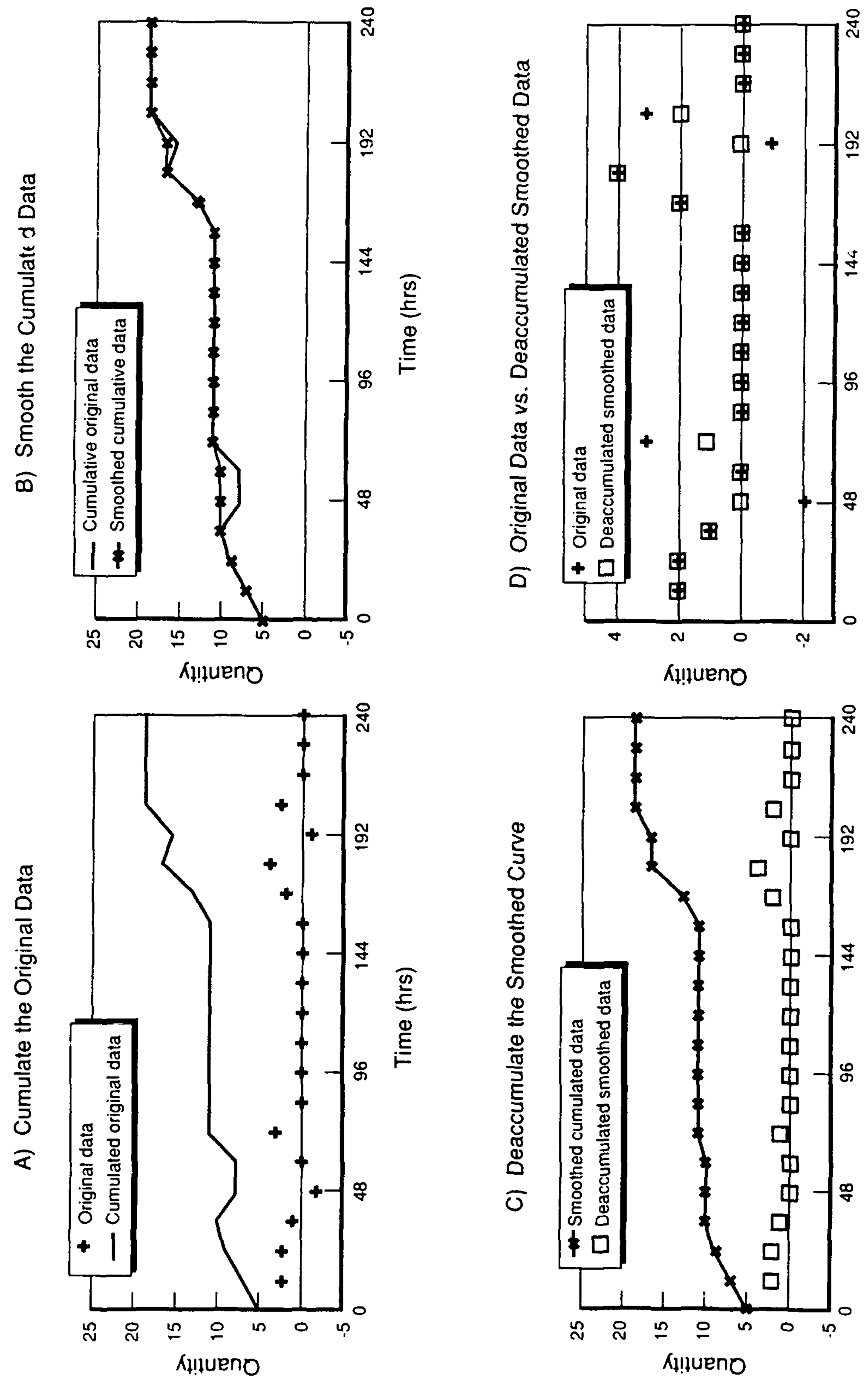

Fig. 2.7—Smoothing the TIME_PHASE Data

done by adding the following records to the TIME_PHASE file at the earliest simulation cycle:

BRIGADE	RECOVERY	AUTH	1000	1000
BRIGADE	RECOVERY	ON HAND	1000	1000
BRIGADE	HET	AUTH	1000	1000
BRIGADE	HET	ON HAND	1000	1000
BRIGADE	DRIVER	AUTH	4000	4000
BRIGADE	DRIVER	ON HAND	4000	4000

As described in [3], Chapter 7, the letters in each of these records consist of a three-part name of a resource; the two numbers represent the amount of that resource to be added to the Blue and Red stocks of that resource, respectively.

One may accomplish the same result by removing the recovery and evacuation activities at the BRIGADE echelon. However, if they are left in place, one may later run LDM excursion cases to estimate the effect of shortages of recovery and evacuation assets on combat performance.

COMPARISON AND ADJUSTMENT

The steps just described are used to calibrate LDM to a FORCEM case. Now one must test the calibration by comparing the results of an LDM simulation with data from the FORCEM reports. Generally, LDM and FORCEM will compare poorly the first time this test is made. Then one must adjust the calibration parameters to improve LDM's fit to FORCEM. Comparison and adjustment will be discussed individually in the sections that follow.

Comparing the Calibrated LDM with the FORCEM Calibration Case

There are many quantities in the FORCEM output reports that the LDM model can also generate. Each of these quantities varies over time, from one simulation cycle to the next. The best way to compare the corresponding FORCEM and LDM quantities is to create a graph, in which the horizontal axis is time and the vertical axis is the quantity being compared. Both the FORCEM and the LDM quantity should be plotted on the same graph. Figure 2.8 shows several examples of these graphs, comparing tanks engaged and hit on both sides in the test case. (By total hits, we mean the sum of permanent and temporary losses.)

When we have calibrated LDM to a FORCEM case, we have always estimated the quality of the fit by eye. We have not applied sophisticated statistical tests because we do not know which statistical test would be appropriate.

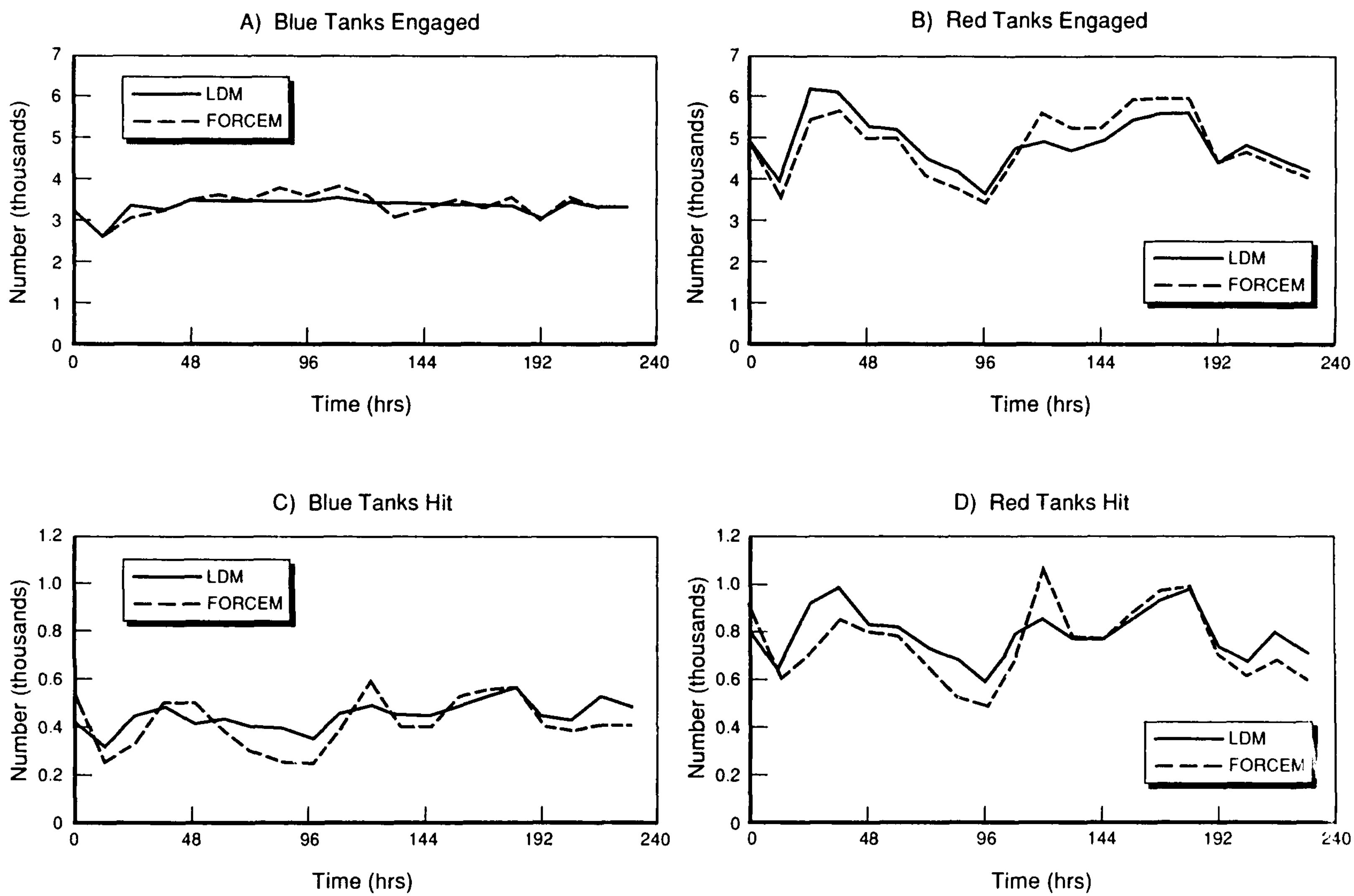

Fig. 2.8—Comparison of LDM and FORCEM

The true test of the fit's quality is how well LDM mimics the results from FORCEM, not only in the case to which it is calibrated, but also in other cases in which quantities of resources have been changed from those in the calibration case. Ideally, one would have several FORCEM cases with which to compare LDM results. In practice, only one FORCEM case is available.

In lieu of using multiple FORCEM cases, we consider each time period in the calibration case as a different minisimulation. In the different time periods, the two sides have different quantities of resources available, engage different inventories of weapons, suffer different losses, and consume different amounts of resources. If LDM's results match those from FORCEM, time period by time period, we can reasonably expect that LDM will respond to changes in resource quantities much as FORCEM would do. But it is not enough for LDM's average losses or average resource consumption in a single case to match those of FORCEM.

An appropriate statistical test of how well LDM mimics FORCEM would have to take this into account. But any statistical test would operate by comparing summary statistics calculated from the LDM and FORCEM results. Those summary statistics must be chosen to retain all the important features of the results while summarizing out only unimportant features. In the present case, so many features of the LDM and FORCEM results are important that none of the usual statistical tests appears to meet this criterion.

However, judging a fit by eye offers no easy way to describe the quality of the fit to others, so the user may wish to find or devise a test that can be applied without using personal judgment.

Resources On Hand at BRIGADE. The first quantities to compare are the resources on hand at the BRIGADE echelon over time. The FORCEM quantities can be obtained from the COMBO and ENGFRAC files, by summarizing resources over all divisions and fractions of divisions engaged in the U.S. portion of the theater. The LDM quantities can be obtained by including the appropriate records in an OUT_SPEC file (see [3], Chapter 6), namely[9]:

```
side    INITIAL    BRIGADE    resource    ON HAND
```

There should be one record for each combination of a "side" and a "resource."

[9]In each record, the user fills in BLUE or RED for "side", and a resource type (e.g., TANK) for "resource." The record tells LDM to output, in each simulated time period, for the "side" the user specifies, the initially available amount of the resource whose three-word name appears in the third, fourth, and fifth fields of the record.

Engaged Weapons. One can also compare the engaged weapons over time. The FORCEM quantities can be obtained from the COMBO and ENGFRAC files, again by summarizing resources over all divisions and fractions of divisions engaged in the U.S. portion of the theater. The LDM quantities can be obtained by using the COMBAT output option in an OUT_SPEC file.

Lack of agreement between FORCEM and LDM engaged weapons is not always due to poor calibration of LDM. In FORCEM, a shortage of ammunition will never prevent a weapon from engaging. Instead, the weapons merely curtail their fire. Thus, if the LDM simulation shows fewer weapons of some type engaged than are found in the FORCEM outputs, one should look at the LDM results to determine whether the number of the weapon engaged is constrained by a shortage of ammunition. If ammunition constraints are severe (i.e., they prevent a large fraction of equipment items from being used as weapons), or if they are persistent (they occur in many simulation cycles), it may be wise to reformulate the weapons in LDM. One can add low-ammunition variants of any weapon type, as discussed in Section 4.

Loss and Consumption of Equipment. FORCEM's estimates of Blue equipment lost or consumed over time may be obtained from Report 64, Loss and Consumption. The data are summarized to the level of the entire theater, but they are presented for each of FORCEM's 51 weapon types. Each of these 51 resources is designated as either a U.S. or a non-U.S. resource. Losses of Blue equipment from the U.S. portion of the theater can be obtained by summarizing the U.S. resources into the groups corresponding to the LDM weapons (see Table 2.3 or 2.4). In Report 64, these losses are split into permanent and temporary losses.

No data in Report 64 allow Red equipment lost to be split between the U.S. and non-U.S. portion of the theater. Therefore, it is necessary to obtain the data by summarizing the losses found in the COMBO file over all Red divisions in the U.S. portion of the theater. The ENGFRAC file provides the fraction of each Red division's losses one should consider suffered in the U.S. portion of the theater. Only total losses can be obtained this way; however, Report 64 provides data to split them into permanent and temporary losses.

LDM equipment losses can be obtained by including the appropriate records in an OUT_SPEC file. Permanent equipment losses can be calculated as the sum of four activity rates, which will be output in response to the following four records:

side	ACTIVITY	BRIGADE	weapon	K-KILL
side	ACTIVITY	BRIGADE	weapon	R-ABAND
side	ACTIVITY	BRIGADE	weapon	E-ABAND
side	ACTIVITY	BRIGADE	weapon	CODE H

Temporary equipment losses can be calculated as the difference between two activity rates, which will be output in response to:

side	ACTIVITY	BRIGADE	weapon	EVACUATE
side	ACTIVITY	BRIGADE	weapon	CODE H

(In the preceding calculation, subtract the CODE H from the EVACUATE activity rate.) These steps must be repeated for every combination of "side" and "weapon."

Loss and Consumption of Personnel. One can obtain FORCEM's estimates of personnel losses in the same way as described for Blue equipment resources. Blue losses come from Report 64, while Red losses come from the COMBO and ENGFRAC files.

LDM's estimates of personnel losses can be obtained by including the following records in an OUT_SPEC file.

side	ACTIVITY	BRIGADE	pers	NET LOSS
side	ACTIVITY	DISCOM	pers	MEDEVAC

The first record will generate permanent losses for personnel type "pers," and the second record will generate temporary losses. These records must be repeated for every combination of "side" and "pers."

Loss and Consumption of Ammunition. FORCEM's estimates of ammunition consumption can be obtained from the same sources as estimates of losses of equipment and personnel. Blue consumption can be found in Report 64, while Red consumption must be taken from the COMBO and ENGFRAC files.

LDM's estimated ammunition consumption can be obtained by including the following record in an OUT_SPEC file:

side	ACTIVITY	BRIGADE	ammo	NET LOSS

This will generate permanent losses only; there are no temporary losses of ammunition. This record must be repeated for every combination of "side" and ammunition type "ammo."

FLOT Movement. Unlike most theater combat models, FORCEM does not explicitly represent the forward line of troops (FLOT). Rather, FORCEM calculates the locations of individual divisions over time. The user must infer the location and rate of movement of the FLOT.

The locations of the divisions can be found in the HDQTRS file, along with a code specifying whether or not the division is engaged (see Table 2.5, which shows the data elements in HDQTRS file). We made maps that locate the U.S. divisions at a given cycle, and we drew lines that mark the forward boundary (in NATO, the eastern boundary) of the area they occupy. We used the average east-west position of this boundary as a measure of FLOT position, and we used the change in this average from one cycle to the next as a measure of FLOT movement.

One problem with this approach is that the north-south extent of the FLOT may change. If it grows—for example, with the introduction of a U.S. corps into a portion of the theater not previously occupied by U.S. forces—one must not average the east-west position of the new section of FLOT with the positions of the old section. If the new section is at a different east-west position, the FLOT will appear to have moved abruptly.

We suggest determining two north-south extents for each cycle, calculating two average FLOT positions (one averaged over each of the north-south extents), and ignoring any occupied area outside those extents. One of the extents should be the largest extent this cycle shares with the previous cycle. The other should be the largest extent it shares with the following cycle. FLOT movement from one cycle to the next is then calculated as the average movement of the FLOT within the extent shared by the two cycles. Figure 2.9 illustrates these calculations.

LDM's estimate of FLOT movement is automatically written to every output file.

Other Potential Comparison Quantities. The preceding quantities comprise all of the quantities we used to compare LDM with the FORCEM case to which it was calibrated.

However, other quantities can also be compared. For example, one could compare quantities of resources on hand at echelons above BRIGADE. The FORCEM estimates of these quantities can be found in Reports 38, 53, and 54. Also, one could also compare numbers of equipment items that undergo maintenance at each echelon and the number of personnel treated in hospitals. FORCEM data on these quantities are in two reports we have not yet mentioned: Report 57, Maintenance; and Report 58, Medical.

Adjusting the Calibration Parameters

Each time that we calibrated LDM to a new FORCEM case, we found that the calibration parameters developed according to the procedures in this section do not yield a very good match. However, they can be adjusted (usually by modest amounts) to improve the match greatly.

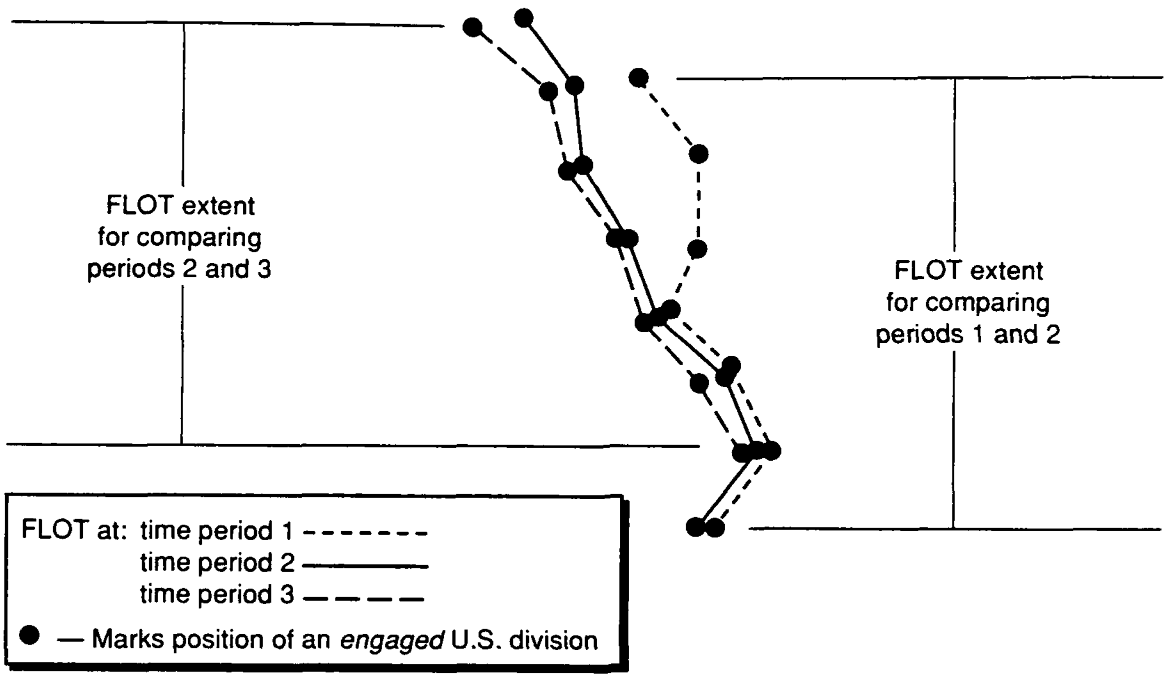

Fig. 2.9—Determining FLOT Movement in a FORCEM Case

This does not mean that one can expect a perfect match. Figure 2.8 illustrates the quality of the match that we have come to expect. LDM cannot match every bump in the FORCEM results, for a variety of reasons. For example, FORCEM distinguishes between day and night, while LDM does not. Some phenomena (e.g., close air support sorties) strongly depend on this. Also, LDM is highly aggregated in comparison with FORCEM. Therefore, it might be wise (although we have never done it) to smooth the FORCEM results, rather than try to match the actual results.

Through experience, we have developed a way systematically to improve the calibration. As a general strategy, we first make the results from the two models match in the early cycles. Then, w adjust parameters to make them agree in later cycles. We work our way through the cycles until the entire simulation matches satisfactorily (or until we admit defeat).

We never adjust more than a few calibration parameters at a time. We run LDM, compare its results with FORCEM, make a few changes, and run LDM again. It has not been possible to predict what effect several simultaneous changes will have. The interactions among the different parameters are simply too strong.

Making Early Simulation Cycles Match. First, we check the quantities of all resources on hand at the BRIGADE echelon. If the calibration was carried out correctly, the LDM and FORCEM quantities should match perfectly at the first simulation cycle.

We also compare quantities of engaged weapons. They should also match closely in the early cycles with the original calibration parameters, although there are a number of reasons that LDM could differ from FORCEM, even at cycle one. For example, it is possible that ammunition shortages limit the number of weapons LDM can make ready for combat. If so, it may be necessary to add low-ammunition variants of weapons in the SUPPORT files, as described in Section 4.

Even if there is ample ammunition, the coefficients in the READY activities, which govern the amounts of resources necessary to make a weapon ready for combat, may be wrong for the first cycle. After all, their values are averages for the entire simulation. This will be a problem only if at least one of the coefficients varies widely from early cycles to late ones and if, at the same time, there is a severe shortage of the resource corresponding to that coefficient. If these conditions apply, consider grouping the 51 FORCEM weapons differently into LDM weapons—i.e., define a new table to replace Table 2.3 or 2.4.

Even if these problems do not appear, the engaged weapons in LDM may differ from those in FORCEM because there should be different engaged fractions for different weapons. This problem cannot be corrected by adjusting the engaged fractions on the TIME records in the TIME_PHASE file (see [3], Chapter 7), because the fractions (one each for Blue and Red) apply equally to all weapons. One way to force a different fraction of each weapon to engage is to modify the SUPPORT files. For example, one could make a different fraction of each type of combat equipment available to be incorporated into weapons. In the test case, this can be accomplished by changing the records that define the WEAPON constraint resources. For tanks, these records are as follows:[10]

CONSTR	BRIGADE	TANK	WEAPON		
RHS	BRIGADE	TANK	ON HAND	1.0	1.0

The coefficients in the RHS record can be replaced by the fractions of Blue and Red tanks the user wishes to make available to be incorporated into weapons. For example, if 90 percent of Blue tanks and 80 percent of Red tanks should be available, the records become:

[10]These two records define a resource called BRIGADE .. TANK .. WEAPON (the CONSTR record) and specify that the amount of this resource should be calculated as 1.0 (coefficients in the RHS record) times the amount of the resource BRIGADE .. TANK .. ON HAND (the RHS record). The two coefficients in the RHS record are used to calculate BLUE and RED resource quantities, respectively.

CONSTR	BRIGADE	TANK	WEAPON		
RHS	BRIGADE	TANK	ON HAND	0.9	0.8

These fractions interact with the engaged fractions on the TIME records. Thus, if the preceding SUPPORT records specify that 90 percent of Blue tanks are available to be incorporated into weapons, and the TIME record specifies that 85 percent of available Blue weapons will be engaged, then at most 90 percent of 85 percent (i.e., 76.5 percent) of Blue tanks on hand can appear on the battlefield. We say "at most" because fewer tanks will appear if a shortage of some other resource (e.g., tank crews) prevents all 90 percent of tanks on hand from being incorporated into weapons.

If both resources on hand at BRIGADE and engaged weapons agree (or have been made to agree) closely in the first few simulation cycles, we next compare total (temporary plus permanent) hits on each equipment type. There is considerable variation in the data from which the attrition functions were developed. Even if the total hits disagree in the first few cycles by as much as 25 percent, there is no problem with scaling the attrition function to make hits match. Generally, different scaling factors should be applied to the attrition functions for different weapons. In scaling the attrition functions, the user does not have to multiply each value by the same constant. He can add (or subtract) a constant, or adjust attrition differently for different postures.

Adjusting the attrition functions to force agreement early in the simulation might cause difficulties in later cycles. The attrition functions were developed using data from all the cycles. Attrition functions developed with data from only the early cycles might be significantly different from functions using data from only late cycles, or all cycles. To avoid this problem, the user might group the 51 FORCEM weapons differently into LDM weapons—i.e., define a new table to replace Table 2.3 or 2.4.

As the next step, we separately compare permanent and temporary losses of each type of equipment. If the LDM quantities do not agree with those from FORCEM in the early cycles, we adjust the appropriate coefficients in the combat loss functions. We do the same for all personnel types and for the different types of ammunition. (Of course, there are no temporary losses of ammunition.)

Making Later Simulation Cycles Match. At this point, all LDM quantities should agree closely with their FORCEM counterparts in the first few simulation cycles. However, the two models may diverge later in the simulation. Any LDM quantity may, over time, drift either above or below the corresponding FORCEM quantity. We first check whether resource shortages force engaged weapons in LDM to be lower than those in FORCEM in the later

cycles. In the FORCEM cases we examined, resource shortages at the BRIGADE echelon develop only after 10 or 20 cycles. The same remedies can be applied for disagreement between LDM and FORCEM in later cycles as were suggested previously for the earlier cycles.

Once engaged weapons match in later cycles, we compare resources on hand at BRIGADE. If they do not match, we adjust parameters in the SUPPORT files, for logistics support can be expected to affect combat performance only after a delay of several cycles. For example, if on-hand resources drift higher in the LDM simulation than in the FORCEM results, they are probably being resupplied at a faster rate than they should. To slow resupply of any resource, one can increase transportation times for that resource. For equipment, one can also (or instead) increase the repair times. For personnel, one can increase the in-hospital times. Conversely, if resources at the BRIGADE echelon drift lower, one can reduce these times.

Other support parameters can also be changed, such as available maintenance man-hours per person. This will have an effect only if, either before or after the change, there are too few maintenance man-hours available to fix all the damaged equipment. Similarly, one may adjust available truck hours per truck to influence transportation. However, in the FORCEM cases we examined, all logistics capacities appeared to be ample almost all of the time, so we generally did not try to make LDM match FORCEM with adjustments of this kind.

In addition, the same kinds of adjustments used to make the first few cycles match can be used again to make later cycles match. Of course, these adjustments will cause the early match to degrade, but one may judge whether the improvement in the later match is worth it.

Making FLOT Movement Match. Once we are satisfied with the match between all other quantities, we adjust the FLOT movement function. We cumulate the FLOT movement estimated by both models to the end of the simulation, and calculate the ratio of the two (FORCEM to LDM). We multiply the FLOT movement function by this ratio; this ensures that LDM's total FLOT movement during the simulation agrees with the FORCEM figure. We make no attempt to adjust the FLOT movement function to make the two models agree at any time except the start (where cumulative FLOT movement is zero) and the end of the simulation.

This adjustment does not affect any other aspect of the LDM simulation. Resources on hand at all echelons, engaged weapons, repair rates—all remain the same regardless of what

is done to the FLOT movement functions. Thus, it is not necessary to revisit the other calibration parameters once the FLOT movement function has been adjusted.

Do not place too much credence on the FLOT movement estimated by LDM. In FORCEM, a division may have to fall back because its neighbor has retreated, even though the division itself faces only weak opposition. Thus, the FLOT movement in the U.S. portion of the theater may depend on what happens in the non-U.S. portion. Obviously, this is not true of LDM, because it models only the U.S. portion of the theater. For this reason, we treat the FLOT movement estimated by LDM as an index of relative overall combat performance, rather than as a measure of territory gained or lost.

3. CALIBRATING LDM TO A CEM CASE

This section is the second of two that deal with calibrating LDM. In the previous section, we discussed how to calibrate LDM to FORCEM results. In this section, we discuss calibrating LDM to CEM results. As mentioned earlier, CEM (Concepts Evaluation Model) is a large theater combat simulation model that has been used for years to provide selected requirements information for building the Army's five-year program. For example, results from CEM have been used to estimate requirements for war reserve equipment and ammunition. While reading this section, and especially while calibrating LDM to CEM, the user should have available the CEM documentation [5, 6].

CEM DATA FILES NEEDED

Together with a team at the Logistics Evaluation Agency (LEA), we have calibrated LDM to one CEM case. Table 3.1 shows the CEM input and output files we used. We obtained these files from the Concepts Analysis Agency (CAA) on magnetic tape, coded as either ASCII or EBCDIC characters. The total size of these files exceeds 300 megabytes, too large to process conveniently on a PC. (The detail report alone accounts for about 99 percent of the data.) A workstation or mainframe computer is recommended for processing these files.

Aggregation

The LDM simulation is much less detailed than the CEM simulation, for several reasons. First, CEM keeps track of many individual Blue and Red units, whereas LDM lumps all forces at a given echelon into a single pool. Second, CEM considers eight different engagement types, which are aggregated into the three LDM postures shown in Table 3.2.

Finally, CEM considers up to 51 different weapon types on each side. These must be aggregated into a smaller number for LDM. Unlike the situation with FORCEM, the 51 CEM weapons can be aggregated in any way desired, because the relevant CEM reports

Table 3.1

CEM Input and Output Files Needed

Input file
Detail report
Logistics report
FEBA location table

Table 3.2

CEM Engagement Types Versus LDM Postures

	CEM Engagement Type	LDM Posture
1.	Blue Attack Delay Defense (BADD)	Blue Attack
2.	Blue Attack Prepared Defense (BAPD)	Blue Attack
3.	Blue Attack Hasty Defense (BAHD)	Blue Attack
4a.	Meeting, Blue Cbt Worth > Red Cbt Worth	Blue Attack
4b.	Meeting, Blue Cbt Worth <= Red Cbt Worth	Red Attack
5.	Red Attack Delay Defense (RADD)	Red Attack
6.	Red Attack Prepared Defense (RAPD)	Red Attack
7.	Red Attack Hasty Defense (RAHD)	Red Attack
8.	Static	Static

contain individual data for each of the 51 weapon types. In the one calibration we performed, we grouped the weapons as shown in Table 3.3. CAA provided data identifying the weapons (e.g., M1, M60A3, and so on) and, for Blue weapons, data specifying their partitions (U.S. Blue or non-U.S. Blue).

Assets other than equipment are considerably more aggregated in CEM than in FORCEM. CEM has only one, rather than six, personnel types.[1] Instead of four ammunition types, CEM has two (artillery and MLRS ammunition, and everything else). Thus aggregating other assets is not a problem. In fact, we tried to disaggregate other assets somewhat.

Preparatory Processing

We have used SAS[2] to carry out the data analysis and file manipulations involved in calibrating LDM to CEM. To prepare for calibration, we split some CEM output reports—

Table 3.3

Aggregation of CEM Weapons

LDM Weapon	U.S. Blue	Non-U.S. Blue	Red
TANK	1–3	4–6	1–8
APC	7–10, 13–19	11–12, 20–24	9–24
HELO	25–28	29	25–29
ATM	30, 32–37	31, 38–41	30–41
INFANTRY	42	42	42
MLRS	43	47	
ARTY	44–46	48–50	43–50

[1]However, CEM assumes that only a specified fraction of available personnel can serve as tank and APC crews.

[2]SAS (the Statistical Analysis System) is a trademark of the SAS Institute, Inc.

which are very large and heterogeneous—into several smaller, more homogeneous files. We also create certain files that will be used in several of the calibration tasks discussed later. Figure 3.1 shows which CEM input and output files contribute data to the files generated during preprocessing.

Splitting the Detail Report

The CEM detail report has a huge number of records (about 2.25 million in the case we used), generated by several different subroutines. All the different record types are mixed together. We extract most of the data from the detail file and place them in five smaller, more homogeneous files, named BLUESEC, REDSEC, ENGAGE, BLUEATT, and REDATT.

Records in each of these files contain a data element for the simulated time. CEM simulates events in several cycles. The shortest cycle is the Division cycle, which is 12 hours. Next comes the Corps cycle, which is a multiple (usually two) of the Division cycle. The Army cycle is a multiple (again, usually two) of the Corps cycle, and the Theater cycle is a multiple (two) of the Army cycle. Time appears in the format Theater/Army/Corps/Division, where "Theater" is replaced by the number of the theater cycle, "Corps" by the number of the Corps cycle, and so on. To determine the LDM time to which a record in the

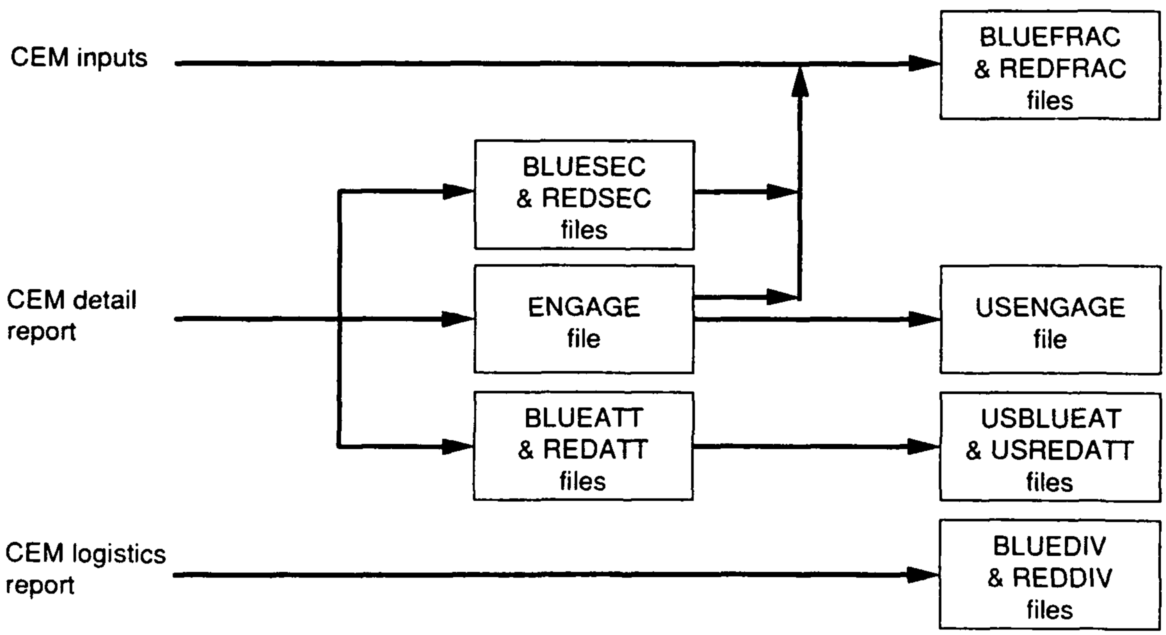

Fig. 3.1—Data Flows in Preprocessing of CEM Files

detail report refers, we locate the most recent time in the detail report, strip off the division cycle number, and multiply by 12.

The BLUESEC and REDSEC Files. The records in the detail file that make up the BLUESEC and REDSEC files describe the location and misson of each Blue and Red unit, respectively. In CEM, the FEBA[3] is divided into as many as 999 *minisectors*; the location of each unit is described by specifying which minisectors it occupies. Missions are ATTACK, DEFEND, DELAY, or RESERV. A unit on either side with a RESERV mission will not occupy any minisectors. A unit that is not in reserve must occupy a contiguous set of minisectors. Table 3.4 shows a sample of the first 30-odd columns of the kinds of records in the detail file that are used to build the BLUESEC and REDSEC files.

The BLUESEC and REDSEC files also show the echelon (i.e., level of the command hierarchy) at which a unit is placed. There are four echelons for Blue (Army, Corps, Division, and Brigade), and three echelons for Red (Army, Corps, and Division). The echelon is not only named but can also be deduced from the locations of the units. For if the minisectors occupied by one unit include minisectors occupied by another, the second unit is

Table 3.4

Detail Record Types for the BLUESEC and REDSEC Files

		Blue Side		
		Minisectors		
Unit		Low	High	Mission
ARMY 1		1	230	DEFEND
CORPS 1		1	81	DELAY
DVSN 1		1	27	
BDE	1	1	8	DELAY
BDE	2	9	19	DELAY
BDE	3	20	27	DELAY
		Red Side		
		Minisectors		
Unit		Low	High	Mission
ARMY 1		1	70	DEFEND
CORPS 1		1	70	DELAY
DVSN	1	1	20	DELAY
DVSN	2	21	40	DELAY
DVSN	3	41	55	DELAY
DVSN	4	56	70	DELAY
DVSN	55	0	0	RESERV

[3]In CEM, the term FEBA (Forward Edge of the Battle Area) is used in place of FLOT.

subordinate to the firs.. Table 3.5 shows the data elements in the BLUESEC and REDSEC files.

The ENGAGE File. The ENGAGE file contains data on each engagement. Its data elements come from several kinds of records in the detail file. Table 3.6 shows a sample of the first few of these record types. Each engagement occurs within a contiguous set of minisectors (called SUBSECTOR in the sample records). The engagement referred to in the sample occurs in minisectors 1 through 18. Each engagement occurs between a Blue brigade (or part of a brigade) and a Red division (or part of a division). The identification numbers of these units occur on the lines that begin with BLUE DIV and RED DIV. This engagement pits Blue brigade 2 against Red division 1. The engagement type is "8" (Static) (see Table 3.2), and the terrain type is "A."

These records are followed by the types of records that provide data for the BLUEATT and REDATT files (to be discussed next). Then there is another group of records that provide data for the ENGAGE file. Table 3.7 shows a sample of these records. Lack of width of these pages has forced us to truncate these records. The FINAL FORCE RATIO record actually contains the following seven numbers, in order:

Table 3.5

Data Elements in the BLUESEC and REDSEC Files

Data Element
Time
Echelon
Unit Number
Low Minisector
High Minisector
Mission

Table 3.6

Some Detail Record Types for the ENGAGE File

```
                        SUBSECTOR    1        18
               BLUE DIV    1            BDE    2       FRONTF1.00    STATE100
               RED DIV   1                             FRONTF  .86   STATE100
ENGAGEMENT TYPE =   8                    TERRAIN = A
                                        QUIET -
OLDIMP SIDE 1:           .27184                    .60161-001        .00000
OLDIMP SIDE 2:           .14515                    .18157            1.0471
```

Table 3.7

More Detail Record Types for the ENGAGE File

FINAL FORCE RATIO	.0000	77.6440	148.5289
FEBA MOVEMENT BEFORE ADJUSTMENT:			0
RED CAS SQDRNS IN DS=	1.00 (WHOLE DIV),	LOSS RATE =	
BLUE CAS SQDRNS IN DS=	0.70 (WHOLE BDE),	LOSS RATE =	

- The ratio of Red-to-Blue initial combat worth engaged (i.e., at the start of this engagement);
- The Blue initial combat worth engaged;
- The Red initial combat worth engaged;
- The Blue combat worth hit in this engagement;
- The Red combat worth hit in this engagement;
- The percentage of the Blue initial combat worth engaged that survived unhit;
- The percentage of the Red initial combat worth engaged that survived unhit.

The data elements in the ENGAGE file are shown in Table 3.8. It should be evident from the preceding discussion which data elements are taken from which types of records.

The BLUEATT and REDATT Files. These files contain attrition data and ammunition consumption data for each engagement. Table 3.9 shows a sample of the detail report records from which these files are constructed. This sample starts with the same first group of records that provide data for the ENGAGE file. From these records come the minisectors for this engagement, the Blue and Red unit numbers, the engagement type, and the terrain type.

The records that follow specify the amounts of ammunition expended by each weapon in the engagement, as well as the number of that weapon type hit in the engagement. Note that each weapon has two "tubes," which means that it can fire two different kinds of ammunition. Rounds fired by each tube type are reported separately. In this sample, the right half of these records has been truncated for lack of space. The right half of each record

Table 3.8

Data Elements in the ENGAGE File

Data Elements	
Time	Blue Bde Number
Low Minisector	Blue Initial Cbt Worth
High Minisector	Blue Cbt Worth Lost
Engagement Type	Red Bde Number
Terrain Type	Red Initial Cbt Worth
Unadjusted FEBA Mvt	Red Cbt Worth Lost

Table 3.9

Detail Record Types for the BLUEATT and REDATT Files

SUBSECTOR 1 18

	BLUE DIV	1	BDE	2	FRONTF1.00	STATE100		
	RED DIV	1			FRONTF .86	STATE100		
ENGAGEMENT TYPE=	8		TERRAIN = A					
			QUIET -					
OLDIMP SIDE 1:	.27184			.60161-001		.00000		
OLDIMP SIDE 2:	.14515			.18157		1.0471		
						ENGAGEMENT EXPE		

SIDE BLUE

		AMMO			WEAPONS	
WPN TYPE	TUBE TYPE	ROUNDS/WPN/TUBE ALLOWABLE	ON-HAND	TOTAL EXPENDED	TOTAL ENGAGED	HIT
4	1	1.38	.00	.00	.00	.00
	2	.74	.00	.00		
5	1	1.18	1.18	20.35	89.00	.46
	2	.12	.12	1.60		

(i.e., to the right of the vertical line of asterisks) includes the same data for Red as the left half shows for Blue. These records continue until all weapon types engaged on either side have been reported.

The data elements in the BLUEATT and REDATT files are given in Table 3.10. It should be evident which data elements come from which records in the detail file. Units are referred to as "Friendly" or "Enemy" in these files. In BLUEATT, a friendly unit is Blue and an enemy unit is Red. In REDATT, this is reversed.

Selecting the U.S. Portion of the Theater. Because we are interested only in U.S. logistics, and U.S. logistics supports only U.S. units, we selected the U.S. units from all Blue units and an appropriate subset of the Red units to serve as the U.S. enemy.

Table 3.10

Data Elements in BLUEATT and REDATT Files

Data Elements	
Time	No. Weapons Engaged
Low Minisector	No. Weapons Hit
High Minisector	Rds On Hand per Tube 1
Friendly Unit No.	Rds Allowed per Tube 1
Enemy Unit No.	Tot Rds Exp by Tube 1
Engagement Type	Rds Allowed per Tube 2
Terrain Type	Rds On Hand per Tube 2
Weapon No.	Tot Rds Exp by Tube 2

The easiest way to determine which Blue brigades are U.S. brigades is to ask CAA. But this can also be deduced from the CEM input data. "Blue Division" records, one of the CEM input record types, specify the Blue forces in the theater. The partition of the division (1=U.S. Blue, 2=non-U.S. Blue) is in column 72 of these records. (Red units are input on records with different formats.)

Each Blue division consists of three Blue brigades,[4] which will belong to the same partition to which the division belongs. The "Blue Brigade" records (records that describe these brigades) do not contain the brigade numbers found in the CEM output files. However, the brigades are numbered in their order of occurrence in the inputs. If one carefully counts the brigades in the inputs, one can discover which brigade numbers belong to the U.S. partition.

We create three more files, containing data for only those engagements in which U.S. units are involved. The files are USENGAGE, USBLUEAT, and USREDATT—subsets of ENGAGE, BLUEATT, and REDATT, respectively. Their formats are the same as the formats shown in Tables 3.8 and 3.10.

The BLUEFRAC and REDFRAC Files

We construct the BLUEFRAC and REDFRAC files to contain, for each unit, the aggregated (i.e., LDM) resources and combat worth owned by that unit when it initially enters the simulation. Ideally, these files would contain, for each unit at each simulation cycle, the resources and combat worth owned by that unit. However, these quantities are not readily available from the CEM reports, so we make do with the initial quantities. The files also contain the fraction of the unit engaged in, and the fraction of the unit assigned to, the U.S. portion of the theater.

The LDM resources and combat worth owned by each unit (division or nondivisional artillery unit) when it enters the theater can be calculated just from CEM inputs; no reference to output reports is necessary. The CEM inputs define the resources in each unit in two stages. First, each unit is expressed as a combination of different types of battalions. Then, each battalion type is described in terms of the quantities of resources (weapons, personnel, supplies) it possesses initially.

Battalion types for both sides are defined in "Maneuver Battalion Type Definition" records (for artillery, "Arty Battalion Type" records). For Blue, the numbers of each type of battalion in each combat unit are given in "Corps Cav Unit" records, "Blue Division" records,

[4]A two-brigade division is possible, but in CEM it is rounded out to three brigades by a "ghost" brigade.

"Division Cav Unit" records, "Blue Brigade" records, and, for artillery, "Initial Nondivisional Artillery Counts" records and "Artillery Arrival Schedule" records. For Red, the numbers of each battalion type per combat unit can be found in "Red Division" records, "Red Regiments" records, and, for artillery, "Initial Nondivisional Artillery Counts" records and "Artillery Arrival Schedule" records. Blue and Red divisions arrive in the theater according to the schedules given in CEM's "Reinforcing Division(s) Arrival" input records.

Next we want to determine the fractions of units assigned to, and engaged in, the U.S. portion of the theater in each simulation cycle. We call these the *unit fraction assigned* (UFA) and *unit fraction engaged* (UFE), respectively; they are calculated similarly to the analogous quantities during the calibration of LDM to FORCEM (see Section 2). For a U.S. brigade, the UFA in any simulation cycle is zero if the brigade has not yet entered the theater; it becomes one once the unit has entered the theater. The UFE can be found from the BLUESEC file. A U.S. brigade has a UFE of zero in a cycle if its mission in that cycle is RESERV (see Table 3.4); otherwise it is one. No intermediate fractions occur in the CEM case we have dealt with, because if any part of a unit is engaged, all of it is considered to be engaged.

It is more difficult to determine the assigned and engaged fractions for a Red division because we wish to determine when the unit, or part of it, is assigned or engaged in the U.S. portion of the theater. We are not interested in when it enters or engages in any part of the theater. We determine the UFE and UFA for a Red division from the REDSEC and ENGAGE files. For each Red division "i" in each cycle "t" we define three fractions:

$F1_{it}$ = fraction of Red division "i" engaged with U.S. brigades in cycle "t"

$F2_{it}$ = fraction of Red division "i"engaged with non-U.S. brigades in cycle "t"

$F3_{it}$ = fraction of Red division "i" not engaged in cycle "t"

If the division has a RESERV mission according to the REDSEC file, we set $F3_{it} = 1$ and $F1_{it} = F2_{i\,t} = 0$. Otherwise, $F1_{it}$ is the ratio of the number of minisectors in which the division is engaged with U.S. brigades (taken from the ENGAGE file), divided by the total number of minisectors the division occupies (taken from the REDSEC file). Similarly, $F2_{it}$ is the ratio of the number of minisectors in which the division is engaged with non-U.S.

brigades, divided by the total number of minisectors the division occupies. And $F3_{i\,t} = 1 - F1_{it} - F2_{it}$.

The UFE of the Red division is just the fraction engaged with U.S. brigades, or:

$$UFE_{it} = F1_{it} \tag{3.1}$$

The UFA is more difficult to calculate. Logically, the fraction assigned to the U.S. portion of the theater cannot be less than the fraction engaged there, nor can it be larger than the fraction not engaged outside the U.S. portion of the theater. That is:

$$F1_{it} \leq UFA_{it} \leq 1 - F2_{it} \tag{3.2}$$

where UFA_{it} is the fraction of Red unit "i" assigned to the U.S. portion of the theater in time period "t." The values we select for UFA in the different cycles can be arbitrary, so long as they are in this range. In the first cycle, we set UFA equal to the fraction of the division engaged in the U.S. portion of the theater. In later cycles, we choose UFA so that it will change as little as possible. This rule is embodied in the following expressions:

$$UFA_{i1} = UFE_{i1} \tag{3.3a}$$

$$UFA_{it} = \mathrm{Min}\{\, \mathrm{Max}\{\, UFA_{i,t-1}, F1_{it} \,\}, (1 - F2_{it}) \,\} \quad (\text{for } t > 1) \tag{3.3b}$$

(In our CEM case, we found that whenever any part of a division was engaged, all of it was engaged. That is, either $F3_{it} = 0$ or $F3_{it} = 1$, never any fraction in between. This makes possible some minor simplifications.)

The engaged and assigned fractions for Blue and Red artillery units cannot be calculated from the BLUESEC, REDSEC, and USENGAGE files. In each cycle, we set these fractions equal to the overall theater engaged and assigned fractions for Blue brigades and Red divisions, respectively. We calculate these overall fractions as follows. Define:

$$CW_i = \text{combat worth of unit "i"}$$

Then:

$$\text{Arty Engaged Fraction} = \Sigma[UFE_{it}CW_i]/\Sigma[CW_i] \tag{3.4a}$$

$$\text{Arty Assigned Fraction} = \Sigma[UFA_{it}CW_i]/\Sigma[CW_i] \tag{3.4b}$$

where all summations are taken over units "i," and the cycle "t" is held constant. (That is, the equations are evaluated once again for each cycle "t.") There are separate equations for

Blue and for Red; for Blue, the summations are over all brigades; for Red, they are over divisions.

Finally, we construct the change in the unit fraction assigned from one cycle to the next. This quantity will be used to calculate the rate of entry into the theater of resources owned by units. This quantity is:

$$DUFA_{i1} = UFA_{i1} \qquad \text{(first simulation cycle)} \qquad (3.5a)$$

$$DUFA_{it} = UFA_{it} - UFA_{i,t-1} \qquad \text{(all later cycles)} \qquad (3.5b)$$

Table 3.11 shows the data elements in the BLUEFRAC and REDFRAC files. In BLUEFRAC, the unit may be a U.S. brigade or a nondivisional artillery unit. In REDFRAC, it may be a Red division or a nondivisional artillery unit. As a reminder, the assigned and engaged fractions are the fractions assigned to and engaged in the U.S. portion of the theater, respectively.

The Logistics Report

The CEM logistics report is described in the CEM VI Users' Handbook. We extract two files from it—BLUEDIV and REDDIV—for use in calibrations. Each file contains data on each of the 51 CEM weapon types and on personnel, POL, nonartillery ammunition, and artillery ammunition. The Blue files record U.S. and non-U.S. personnel and ammunition separately.

Table 3.11

Data Elements in the BLUEFRAC and REDFRAC Files

Time
Unit
Unit fraction engaged (UFE)
Unit fraction assigned (UFA)
Change in unit fraction assigned (DUFA)
Initial combat worth (CW)
Initial number of TANKs
Initial number of APCs
Initial number of HELOs
Initial number of ATMs
Initial number of MLRSs
Initial number of ARTYs
Initial number of Personnel
Initial quantity of Non-Arty Ammunition
Initial quantity of Arty Ammunition
Initial quantity of POL

The logistics report records for the division cycles contain the total temporary and permanent losses of each weapon from the beginning of the simulation through the current time period. We "deaccumulated" these losses—i.e., subtracted the losses reported at the ends of successive time periods—to obtain the incremental losses that occurred during each time period.

The data elements in the BLUEDIV and REDDIV files are shown in Table 3.12.

DEVELOPING DATA FOR THE ATTRITION FILE

The ATTRITION file contains six different kinds of data (see [3], Chapter 4). Five kinds of data are obtained by manipulating CEM input and output data. These five are posture functions, FLOT movement functions, combat worth coefficients, attrition functions, and combat loss coefficients. The other kind of data in the ATTRITION file—the specification of combat worth ratio categories—requires no data analysis. Figure 3.2 shows which CEM files are used to develop the data in the LDM ATTRITION file, as well as the other LDM input files.

Combat Worth Ratio (CWR) Categories Data

These data specify the categories into which LDM will partition combat worth ratios (i.e., the CWR categories). They should be left as they are in Appendix A, Table A.1.

Posture Data

The posture functions are generated from data in the USENGAGE file. We compute the ratio of Blue to Red combat worths in each engagement, and assign each engagement to a CWR category and a posture, based on the CEM engagement type (Table 3.2). Finally, we create a two-way table whose rows and columns correspond to CWR categories and LDM postures, respectively. Each cell in the table contains the sum of combat worth (Red plus

Table 3.12

Data Elements in the BLUEDIV and REDDIV Files

Time
Resource
Quantity authorized
Quantity on hand after resupply
Quantity available before resupply
Quantity required before resupply
Temporary combat losses, this division cycle
Permanent combat losses, this division cycle
Temporary noncombat losses, this division cycle
Permanent noncombat losses, this division cycle

	Attrition					Support	Time_Phase			
	Posture data	FLOT movement	Cbt. worth coeffs	Attrition tables	Cbt. loss coeffs	READY activities	Engagement fracs	Std. deviations	Unit resources	Theater resupply
USENGAGE file	X	X		X				X		
USBLUEAT file				X	X					
USREDATT file				X	X					
BLUEFRAC file							X		X	
REDFRAC file							X		X	
BLUEDIV file			X		X	X				
REDDIV file			X		X	X				
CEM inputs					X	X				X

Fig. 3.2—CEM Data Sources for the LDM Input Files

Blue) in all the engagements that have the appropriate posture and combat worth ratio category.

Each cell also contains the fraction that the entry represents of the row total. These fractions form the posture data that appear in the ATTRITION file. They can be used as is, or plotted for each posture separately as a function of combat worth ratio and then smoothed.

FLOT Movement

The USENGAGE file contains the "unadjusted" FLOT movement for each engagement. This is the movement of the units in that engagement, without regard for how neighboring units may move. Later in the simulation cycle, CEM adjusts the FLOT movement so that a unit whose neighbors retreat also falls back, thus keeping the FLOT more or less straight.

Each engagement can be assigned to a CWR category and a posture, as described previously. We calculate the average unadjusted FLOT movement for each combination of CWR category and posture. These averages can be used directly as the FLOT movement

function, or they can be plotted for each posture separately and smoothed. Unlike FORCEM, the Blue and Red FLOT movement functions will be the same (i.e., the attacker will advance the same distance as the defender retreats).

The Combat Worth Coefficients

The combat worth coefficients are calculated, for each LDM weapon on each side, by averaging the combat worths of the appropriate groups of CEM weapons. Table 3.3 shows how the 51 CEM weapons were grouped into LDM weapons. We simply form weighted averages of the CEM combat worths of the weapons in a group, using the theaterwide inventories of those weapons as the weights. The inventories come from the BLUEDIV and REDDIV files. The combat worth coefficients for the CEM weapons can be found in the "weapon description" records (and for artillery, in the "Arty cannon type" records) of the CEM input file. In those records, they are called "weapon values."

As an example, consider how to compute the combat worth coefficient for U.S. tanks. From the inputs, the combat worths of the three CEM weapons that make up a U.S. TANK in LDM are 0.722, 0.539, and 0.312, respectively. The numbers of these three CEM weapons at division cycle 1 are 1460, 475, and 81, respectively, as reported in BLUEDIV. At division cycle 1, the average combat worth for U.S. TANKs in LDM is calculated as follows:

$$(1460 \times 0.722 + 475 \times 0.539 + 81 \times 0.312)/(1460 + 475 + 81) = 0.6224$$

We form separate averages for each division cycle, and then calculate the means and standard deviations over all cycles. The coefficients used in LDM should be the means over all cycles.

Attrition Data

For each weapon system in LDM, there are three attrition functions (one for each engagement type—Blue Attack, Red Attack, and Static). Each attrition function relates the fraction of an engaged weapon system that will be hit to the ratio of Blue to Red combat worth in the engagement. Table 3.2 shows how the eight CEM engagement types are mapped into the three LDM postures, while Table 3.3 shows how the 51 CEM weapon types are grouped into the 7 LDM weapon types. Given these tables, we developed the attrition functions from the files USREDATT, USBLUEAT, and USENGAGE.

To develop the Blue attrition functions, we aggregate weapon systems engaged and hit in USBLUEAT into LDM weapon types, postures, and CWR categories. Then we calculate the ratio of hits to engaged weapons and plot the fraction hit versus CWR category for each weapon type and posture. These can be used directly as the Blue attrition

functions, or they can be smoothed first. We do the same for the Red attrition functions, but use the USREDATT file in place of USBLUEAT. It is important to note that the 51 Red CEM weapons can be aggregated differently into LDM weapon types than the Blue CEM weapons.

Unlike with FORCEM, no extra step is required to obtain the attrition functions for infantry. The engaged and hit numbers of infantry are reported in the USBLUEAT and USREDATT files, just as are the engaged and hit numbers of other CEM weapons.

Combat Loss Coefficients

K-Kills, M-Kills, and F-Kills of Equipment. We calculate the fractions of hits on each weapon that were K-kills, M-kills, and F-kills as follows. The BLUEDIV and REDDIV files contain both temporary and permanent combat losses of each weapon at each division cycle (as listed in Table 3.12). To estimate the fraction of hits on an LDM weapon that were K-kills, we take the ratio of permanent combat losses to permanent plus temporary combat losses for all CEM weapons in the group corresponding to the LDM weapon. CEM does not distinguish between M-Kills and F-Kills, so we split the temporary losses in the same proportions as in the most recent FORCEM case.

Personnel Wounded and Lost. The number of crew killed and wounded per weapon hit is found in the CEM "Weapon Description" input records for most of the 51 weapon types (see the CEM VI Users' Handbook). We form weighted averages of these coefficients for each group of CEM weapons that corresponds to an LDM weapon (see Table 3.3). The weights were the theaterwide on-hand inventories for each division cycle, as found in the BLUEDIV and REDDIV files. We form separate averages for each division cycle, and then calculate the means and standard deviations over all cycles. The coefficients used in LDM should be the means over all cycles.

We take the fraction of hits on infantry that were kills to be the ratio of permanent personnel losses to permanent plus temporary losses from the BLUEDIV and REDDIV files. This is not totally correct because the personnel losses in these files include losses among TANK, APC, and HELO crews, which we do not want to include among LDM's INFANTRY. However, most casualties are probably among the infantry, so the error is relatively small.

An alternative approach would use CEM input data from the CONSTANT section of the CEM inputs. In particular, the PERSNKIA and PERSNWIA records give fractions of casualties killed and wounded in action, respectively. There is a different factor for each engagement type, so they would have to be averaged over engagements in the USBLUEAT and USREDATT files. Also, the fraction killed plus the fraction wounded does not

necessarily equal one because some losses are captured or missing in action. In LDM, these should probably be lumped with the killed fraction.

Ammunition Consumption. We estimate the coefficients in the combat loss functions for ammunition from the USBLUEAT and USREDATT files, plus certain inputs. We calculate the weight of ammunition consumed by each of CEM's weapons in each engagement by taking the number of rounds fired from USBLUEAT or USREDATT, multiplied by the weight per round and by an ammunition consumption factor, from the CEM input file. Both round weights and ammunition consumption factors can be found in CEM's "Weapon description (ammo rqmts)" records (for artillery, the "Arty DS ammo expenditure" records). There is a different ammunition consumption factor for each weapon type and engagement type. This factor is intended to account for noncombat consumption of ammunition.

We then aggregate the weigh' of ammunition consumed across groups of CEM weapons to obtain ammunition consumed by each LDM weapon. We also aggregate the weapons engaged and weapons hit. Then we regress the ammunition consumed against the engaged and hit weapons, suppressing the constant term in the regression equation. We perform this exercise separately for the two kinds of ammunition fired by each weapon; however, for all weapons except Blue tanks, we combine the results for the two ammunition types.

Some of the regression coefficients may be negative. When this occurs, we set the offending coefficient to zero and recalculate the remaining coefficient.

Most of the ammunition consumption appeared to relate to weapons hit, and much less to weapons engaged. We suggest that when a weapon is in an intense engagement, it shoots more and is more likely to be hit than if the engagement is less intense.

In calibrating LDM to CEM, we retained the four types of ammunition considered in FORCEM. We assumed that Blue TANKs used TANK AMM as their type 1 ammunition and OTHR AMM as their type 2 ammunition. Blue APCs, HELOs, ATMs, and INFANTRY use OTHR AMM as both type 1 and type 2 ammunition. Blue MLRS uses MLRS AMM, and Blue ARTY uses ARTY AMM (we took the "special ammunition" in FORCEM to be MLRS AMM). For Red, we assumed that only two types of ammunition were used. Red ARTY uses ARTY AMM, and everything else uses OTHR AMM.

DEVELOPING DATA FOR THE SUPPORT FILES

The CEM model includes virtually no logistics support structure. Instead, logistics functions are represented in terms of delays and, in the case of equipment, by constraints

that limit the numbers of tanks, APCs, and helicopters of each partition (U.S. Blue, non-U.S. Blue, and Red) that may enter repair in each division cycle. There are delays for repair, as well as for the resupply of equipment, personnel, and ammunition.

For analysis purposes, LDM should have a much more elaborate support structure than CEM. But the user will have to construct it from, and calibrate it to, other sources of data.[5] However, regardless of the source, one cannot expect (and probably would not want) an elaborate LDM support structure to behave as the simple CEM logistics representation behaves. To calibrate LDM to CEM, therefore, the LDM support structure must be "de-tuned," or replaced by a simplified structure during calibration to CEM. The desired LDM support structure can be reinserted after calibration and used during subsequent analyses.

A few coefficients for the SUPPORT files can be obtained from CEM input and output data. These are as follows: the coefficients in the READY activities (activities that combine resources into weapon systems ready to engage); durations of certain classes of activities; maintenance capacities for certain classes of equipment; and the proportion of each equipment type that will suffer RAM (Reliability, Availability, and Maintainability) failures in each division cycle. Figure 3.2 shows which files contribute to the evaluation of coefficients in the READY activities; these are the only coefficients that will not be superseded when a more elaborate logistics structure replaces the simple one used during calibration of LDM to CEM.

Coefficients for the READY Activities

Personnel per READY Weapon. The "Weapon description" records (for artillery, the "Arty cannon type" records) in the CEM inputs include the size of the crew needed for each of the 51 CEM weapon types. For each LDM weapon, we form a weighted average of these coefficients; the weights are the inventories of the CEM weapons found in the BLUEDIV and REDDIV files. The average is taken over all CEM weapons in the group that corresponds to the LDM weapon. We form separate averages for each division cycle, and then calculate the means and standard deviations over all cycles. The coefficients used in LDM should be the means over all cycles.

Ammunition per READY Weapon. The amount of ammunition that the brigade must have on hand for each weapon that it makes ready for combat is not necessarily the amount that the weapon carries. In the CEM case, the inputs specified that brigades should have eight division cycles' worth (i.e., four days' worth) of ammunition on hand; if necessary,

[5]For example, the structure could be borrowed from FORCEM (i.e., the test case), or built from doctrine and planning factors (Sections 4–7 of this Note).

brigades should restrict their ammunition consumption to prevent depleting their supplies below this level. We took the amount of ammunition required per engaged weapon to be eight times the average amount of ammunition expended by that weapon per engagement.

Other Possible Data for the SUPPORT Files

A number of other data elements in the CEM inputs might be useful in calibrating LDM. (However, remember that the support structure that allows LDM to match CEM results will be too simple for the kind of analysis LDM is designed to do. Once LDM is calibrated, the simple support structure must be modified or replaced.) The "Maintenance Capacity" records contain repair capacities. The durations of activities that transport ammunition and other supplies may be obtained from the "Theater Resource Delay" record. Delays for assimilation of resources of all kinds can be found in the "Personnel Assimilation Fractions" and "Supply Absorption Limit" records.

DEVELOPING DATA FOR THE TIME_PHASE FILE

The TIME_PHASE file ([3], Chap. 7) contains three sorts of data. The TIME records contain the Blue and Red fractions of available weapon systems that are engaged in each simulation cycle, as well as the standard deviations of the combat worth ratio distribution. The other records in the TIME_PHASE file contain resource quantities that enter the theater at each cycle. Figure 3.2 shows which files are used to develop the TIME_PHASE data. It is helpful to have the TIME_PHASE file for the test case NOMTIME.DAT available as you read this section. Like all files for the test case this file is included in the floppy disks distributed with the LDM Users' Manual [3].

Engaged Fractions

The fractions of available weapons engaged in each simulation cycle are calculated from the BLUEFRAC and REDFRAC files. The equation is as follows:

$$\text{Engaged Fraction} = \Sigma[UFE_{it}CW_i]/\Sigma[UFA_{it}CW_i] \tag{3.6}$$

UFE_{it} and UFA_{it} were defined earlier as the fractions of units engaged in and assigned to the U.S. portion of the theater, respectively. CW_i was defined earlier as the combat worth of unit "i." The summations are taken over all units "i" at a particular cycle "t." The same equation can be used for either Blue or Red.

Standard Deviation of the Combat Worth Ratio Distribution

We use data from the USENGAGE file to estimate the standard deviation of the log-normal distribution of combat worth ratios in each cycle (see Appendix A). The standard deviation governs how much the local combat worth ratios between engaged Blue and Red forces will deviate from the theaterwide average ratio. A higher standard deviation means that a larger fraction of the Blue and Red forces will be engaged at combat worth ratios much larger and much smaller than the theater average. A lower standard deviation means that more of the Blue and Red forces will be engaged at combat worth ratios close to the theater average.

We calculate two sample means and two sample standard deviations of the logarithms of the combat worth ratios of the engagements in each cycle, using standard statistical formulas. There are two of each in each cycle—not one—because the mean and standard deviation can be calculated for the Blue or Red engaged combat worth. If the combat worth ratio distributions of Blue and Red combat worth were perfectly log-normal, the two standard deviations would be identical. Because they are not, we use the average of the two values calculated above.

Quantities of Resources Entering the Theater

Resources Entering in Units. Resources entering the U.S. portion of the theater as part of units can be calculated from the BLUEFRAC and REDFRAC files, using the following formula:

$$DELQ_{rt} = \Sigma[DUFA_{it} Q_{ri}] \tag{3.7}$$

Q_{ri} is the initial quantity of resource "r" in unit "i" from the BLUEFRAC or REDFRAC file. $DUFA_{it}$ is the change in the unit fraction assigned (UFA_{it}) from one time period to the next [see Equations (3.5a) and (3.5b)]. $DELQ_{rt}$ is the total amount of resource "r" in units or fractions of units newly assigned to the U.S. portion of the theater in cycle "t." We have specified that resources entering with combat units are given directly to the BRIGADE echelon. Resources entering with a CSS unit are given to the echelon at which that unit does its work.

Resources Entering as Resupply. To calculate Blue and Red resources entering the theater apart from units (i.e., used to replenish losses from units), we read the LOGISTIC records from the CEM input file, and aggregate the resources from the detailed CEM categories to the LDM categories. LOGISTIC records specify the *theater* cycle during which the resources enter the simulation. In CEM, these resources are spread equally

among the division cycles in that theater cycle. For Blue, resources are identified as being either U.S. or non-U.S. resources; we select only the U.S. resources. For Red, we allocate total resources entering the theater between the U.S. and non-U.S. portions in proportion to the Red forces engaged against U.S. and non-U.S. brigades, respectively. We use only the resources allocated to the U.S. portion of the theater in the LDM simulation. All resources from the LOGISTIC records enter at the THEATER echelon.

Smoothing. Just as we described for FORCEM, we smooth the TIME_PHASE data obtained from the CEM case. The method is the same as described in Section 2.

COMPARING LDM WITH CEM

The steps just described calibrate LDM to a CEM case. After calibrating, one must test the success of the exercise by comparing the results of an LDM simulation with data from the CEM reports. Generally, LDM and CEM will compare poorly the first time this test is made, and one must adjust the calibration parameters to improve LDM's fit to CEM. Adjustment to improve the fit to FORCEM was discussed in Section 2. One must use the same process to improve the calibration to CEM.

The user will find many quantities in the CEM output reports that the LDM model can also generate. Each of these quantities varies over time, from one simulation cycle to the next. They can be compared by plotting the corresponding CEM and LDM quantities on the same graph, where the horizontal axis represents time and the vertical axis represents the quantity being compared.

Resources On Hand at BRIGADE

The first quantities to be compared are the resources on hand at the BRIGADE echelon over time. We obtain the CEM quantities by combining the BLUEDIV and REDDIV files with the BLUEFRAC and REDFRAC files, respectively. Then we summarize resources over all divisions and fractions of divisions engaged in the U.S. portion of the theater. The LDM quantities can be obtained by including the appropriate records in an OUT_SPEC file (see [3], Chapter 6), namely:

side	INITIAL	BRIGADE	resource	ON HAND

There should be one record for each combination of a "side" and a "resource."

Engaged Weapons

One can also compare the engaged weapons over time. The CEM quantities can be obtained from the USBLUEAT and USREDATT files, by summarizing resources over all

engagements (only U.S. engagements are included in these files). The LDM quantities can be obtained by using the COMBAT output option in an OUT_SPEC file.

Lack of agreement between CEM and LDM engaged weapons is not always due to poor calibration of LDM. In CEM, a shortage of ammunition will never prevent a weapon from engaging. Instead, the weapons merely curtail their fire. Thus, if the LDM simulation shows fewer weapons of a particular type engaged than are found in the CEM outputs, one should look at the LDM results to see whether the number of this weapon engaged is constrained by a shortage of ammunition. If ammunition constraints are severe (i.e., prevent a large fraction of equipment items from being used as weapons), or if they are persistent (occur in many simulation cycles), it may be wise to reformulate the weapons in LDM. One can add low-ammunition variants of any weapon type, as discussed in Section 4.

Loss and Consumption of Equipment

CEM's estimates of Blue equipment lost or consumed over time may be obtained from the BLUEDIV file. These data are summarized to the level of the entire theater, but they are presented for each of CEM's 51 weapon types. Each of these 51 resources is designated as either a U.S. or a non-U.S. resource. Losses of Blue equipment from the U.S. portion of the theater can be obtained by summarizing the U.S. resources into the groups corresponding to the LDM weapons (see Table 3.3). In the BLUEDIV file, these losses are split into permanent and temporary losses.

No data in the REDDIV file allow Red equipment lost to be split between the U.S. and non-U.S. portion of the theater. Therefore, one must obtain these data by summarizing the losses found in the USREDATT file. Only total losses can be obtained this way, but the REDDIV file provides data to split them into permanent and temporary losses.

LDM equipment losses can be obtained by including the appropriate records in an OUT_SPEC file. Permanent equipment losses can be calculated as the sum of four activity rates, which will be output in response to the following four records:

side	ACTIVITY	BRIGADE	weapon	K-KILL
side	ACTIVITY	BRIGADE	weapon	R-ABAND
side	ACTIVITY	BRIGADE	weapon	E-ABAND
side	ACTIVITY	BRIGADE	weapon	CODE H

Temporary equipment losses can be calculated as the difference between two activity rates, which will be output in response to the following two records:

side	ACTIVITY	BRIGADE	weapon	EVACUATE
side	ACTIVITY	BRIGADE	weapon	CODE H

(Subtract the CODE H from the EVACUATE activity rate.)

These records must be repeated for every combination of "side" and "weapon." (These activity names are the ones used in the test case. If a different support structure is used, with different SUPPORT files, it may be appropriate to specify different activities to output.)

Loss and Consumption of Personnel

CEM's estimates of personnel losses are more difficult to determine from available reports. U.S. losses come from the BLUEDIV file. However, there is no good way to determine Red losses in the U.S. part of the theater. Infantry losses can be obtained from the USREDATT file. Or total personnel losses can be taken from the REDDIV file, and then split according to the fractions in the REDFRAC file, a procedure that is not entirely satisfactory.

LDM's estimates of personnel losses can be obtained by including the following records in an OUT_SPEC file.

side	ACTIVITY	BRIGADE	pers	NET LOSS
side	ACTIVITY	DISCOM	pers	MEDEVAC

he first of these records generates permanent losses of personnel type "pers," while the second record generates temporary losses. These records must be repeated for every combination of "side" and "pers."

Loss and Consumption of Ammunition

CEM's estimates of ammunition consumption can be obtained as follows. U.S. consumption can be found in BLUEDIV. Red consumption can be calculated from USREDATT.

LDM's estimated ammunition consumption can be obtained by including the following record in an OUT_SPEC file:

side	ACTIVITY	BRIGADE	ammo	NET LOSS

This will generate permanent losses only; there are no temporary losses. This record must be repeated for every combination of "side" and ammunition type "ammo."

FLOT Movement

CEM gives the FLOT location in each minisector at each division cycle in the FEBA Location Table, one of the CEM output reports. If the same minisectors were always in the

U.S. portion of the theater, one could simply average the FLOT position across the U.S. minisectors in each cycle, and observe the movement from cycle to cycle. However, a minisector can change from non-U.S. to U.S. or vice versa (for example, with the introduction of a U.S. corps into a portion of the theater not previously occupied by U.S. forces). One must not average the FLOT position in the new minisectors with that of the old; if the FLOT in the new minisectors is at a different position, the FLOT will appear to have moved abruptly. We suggest determining the FLOT movement from one cycle to the next by determining which minisectors are U.S. minisectors in both cycles, and by averaging the difference in the FLOT positions only over those minisectors.

LDM's estimate of FLOT movement is automatically written to every output file.

4. ALTERNATIVE REPRESENTATIONS OF WEAPON SYSTEMS

This section discusses a number of modifications and additions one might wish to make to the SUPPORT files for the test case, to model weapon systems more realistically. Before the reader begins this section, we recommend that he review Chapter 5 of the LDM Users' Manual [3], which describes the different types of records in a SUPPORT file and explains their formats and data elements. In the following paragraphs, we discuss how to model weapons so they can engage in combat with either a full crew or a partial one, with a full or reduced load of ammunition, or with either a preferred munition or a less effective substitute. In any of these cases, the effectiveness of one version of the weapon may differ from the effectiveness of the other. We also discuss how one may introduce these possibilities for one side (e.g., Blue) but not the other.

PARTIAL CREWS

Suppose a tank has a normal crew of four but can operate with a crew of only three. To formulate the SUPPORT files to accommodate this variation in crew, one defines multiple variants of the tank weapon. The required records are as follows:[1]

CONSTR	BRIGADE	TOT_TANK	SUM				
PIPE	BRIGADE	TOT_TANK	DUMMY	0.	–10.	0.	–10.
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	TANK AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	3.0		3.0	
COEF	BRIGADE	TOT_TANK	SUM	–1.0		–1.0	
PIPE	BRIGADE	APC	READY	0.	–10.	0.	–10.
FROM	BRIGADE	APC	WEAPON	1.		1.	
FROM	BRIGADE	OTHR AMM	WEAPON	16.8		7.56	
FROM	BRIGADE	WPN CREW	WEAPON	4.		4.	
PIPE	BRIGADE	TANK4	READY	0.	–9.5	0.	–9.5

[1]The CONSTR record defines a resource named BRIGADE .. TOT_TANK .. SUM. Each PIPE record, as well as the FROM and COEF records following it, defines an activity in terms of the amounts of resources it consumes and produces. The activity is named in the PIPE record, which also specifies the activity's durations and priority numbers for BLUE and RED, respectively. For example, the first PIPE record names the BRIGADE .. TOT_TANK .. DUMMY activity, and defines the activity to have a duration of 0 hours and a priority number of –10, for both BLUE and RED. Each FROM or COEF record names a resource that is produced or consumed by the activity, and specifies the amounts consumed or produced by the BLUE and RED versions of this activity per period, at activity rates of 1.0. Resources with positive coefficients are consumed, while resources with negative coefficients are produced. For example, the first COEF record tells LDM that each unit of the BLUE activity BRIGADE .. TOT_TANK .. DUMMY will consume 52.6 units of the BLUE resource BRIGADE .. TANK AMM .. WEAPON. The corresponding RED activity will consume 29.2 units of the same RED resource.

COEF	BRIGADE	WPN CREW	WEAPON	1.0		1.0	
COEF	BRIGADE	TOT_TANK	SUM	1.0		1.0	
PIPE	BRIGADE	TANK3	READY	0.	–9.4	0.	–9.4
COEF	BRIGADE	TOT_TANK	SUM	1.0		1.0	

When LDM calculates them, the rates of these activities will have the following interpretations:

- BRIGADE .. TOT_TANK .. DUMMY will equal the total number of tanks available for combat;
- BRIGADE .. APC .. READY will equal the total number of APCs available for combat;
- BRIGADE .. TANK4 .. READY will equal the number of tanks with crews of four available for combat; and
- BRIGADE .. TANK3 .. READY will equal the number of tanks with crews of three available for combat.

The records just listed define a portion of the activity matrix (see Appendix B) for each side. For Blue, that portion looks like the following:

		Activity			
Resource	Initial Quantity	TOT_TANK (p=–10.)	APC (p=–10.)	TANK4 (p=–9.5)	TANK3 (p=–9.4)
TANK	100.	1.0	—	—	—
APC	100.	—	1.0	—	—
TANK AMM	10000.	52.6	—	—	—
OTHR AMM	10000.	12.0	16.8	—	—
WPN CREW	750.	3.0	4.0	1.0	—
TOT_TANK	0.	–1.0	—	1.0	1.0

We also included in this table a column labeled "Initial Quantity," which represents the quantities of the resources we assume, for the purpose of the example that follows, to be available at the start of a simulation cycle.

As explained in [3], Chapter 6, the priority numbers merely establish the order in which the activity rates are calculated. Their actual magnitudes mean nothing. An activity with a low-priority number will have its rate calculated before an activity with a high-priority number, and hence will have a prior claim on any resources it consumes. Activities

with the same priority number will have their rates calculated simultaneously, so any resource they both consume will be shared between them. The coefficients in the table are the quantities of each resource consumed (if the coefficient is positive) or produced (if the coefficient is negative) at an activity rate of 1.

LDM calculates the rates of these activities in priority order, starting with the lowest-priority number –10.0 (the activities BRIGADE .. TOT_TANK .. DUMMY and BRIGADE .. APC .. READY—called TOT-TANK and APC for short in the preceding table). Appendix B describes in detail how LDM calculates rates of activities with equal priorities; it shows an example with two activities that are almost identical to the two discussed here. We will not repeat that discussion here. Given the initial quantities from the preceding table, LDM will determine each of these activity rates to equal 100. Together, then, they will consume the following amounts of resources:

Resource	Amount Consumed
TANK	100
APC	100
TANK AMM	5260
OTHR AMM	2880
WPN CREW	700
TOT_TANK	–100

The negative consumption of the BRIGADE .. TOT_TANK .. SUM (called TOT_TANK for short) indicats that 100 units of this resource are *produced*. The quantity of this resource is initialized to zero at the start of each simulation cycle because it is defined as a constraint resource (note the preceding CONSTR record) with no accompanying RHS records. Once the two activities with priorities –10.0 have been calculated, there will be 100 units of this resource available for use by activities calculated later (namely, the TANK4 and TANK3 activities).

The TANK4 and TANK3 activities each consume one unit of the TOT_TANK constraint resource. The TANK4 activity, which is the next activity to be calculated, also consumes the BRIGADE .. WPN CREW .. WEAPON resource. Because 750 WPN CREW were available originally, the calculation of the priority –10.0 activities leaves only 50 remaining. Thus, LDM will calculate the activity rate of BRIGADE .. TANK4 .. READY to be 50. This will consume all 50 remaining WPN CREW plus 50 of the 100 TOT_TANK resource.

Finally, LDM will calculate the rate of the TANK3 activity, which consumes only the TOT_TANK resource. Only 50 units of this resource remain, so LDM determines the TANK3 activity to equal 50.

The values of the four activity rates are as follows:

Activity	Rate
TOT_TANK	100
APC	100
TANK4	50
TANK3	50

That is, given the initial quantities of the resources, LDM will make a total of 100 tanks and 100 APCs available for combat. Of the tanks, 50 will have crews of four, while the other 50 will have crews of only three.

TANK3 and TANK4 should be considered variants of the old TANK weapon. They must be defined as weapons in the ATTRITION file, and they need combat worth coefficients and attrition tables. Indeed, if a tank with a crew of three is less effective than one with a crew of four, the ATTRITION file should contain different data for the two variants. However, TOT_TANK is only an intermediate variable and not a weapon. It should not have any attrition data.

REDUCED AMMUNITION LOADS

Just as a tank may be able to operate with a reduced crew, a commander may choose to send it into battle with a reduced quantity of ammunition.[2]

Changes to the SUPPORT File

For simplicity, we will assume that there is no minimum ammunition load that a tank must have to engage. One way to represent the possibility of reduced ammunition loads is with the following SUPPORT file records:

```
CONSTR  BRIGADE  TA_TANK   SUM
CONSTR  BRIGADE  OA_T/APC  SUM
PIPE    BRIGADE  TOT_TANK  READY    0.   –10.   0.   –10.
  FROM  BRIGADE  TANK      WEAPON   1.          1.
  COEF  BRIGADE  WPN CREW  WEAPON   4.0         4.0
```

[2]In fact, CEM and FORCEM (the theater models used by the U.S. Army Concepts Analysis Agency, or CAA) both allow weapons to engage, regardless of how little ammunition they may have. The models then reduce the firing rates of engaged weapons so that ammunition expenditures do not exceed the ammunition available.

COEF	BRIGADE	TA_TANK	SUM	–52.6		–29.2	
COEF	BRIGADE	OA_T/APC	SUM	–12.0		–5.45	
PIPE	BRIGADE	TOT_APC	READY	0.	–10.	0.	–10.
FROM	BRIGADE	APC	WEAPON	1.		1.	
FROM	BRIGADE	WPN CREW	WEAPON	4.		4.	
COEF	BRIGADE	OA_T/APC	SUM	–16.8		–7.56	
PIPE	BRIGADE	TA_TANK	READY	0.	–9.5	0.	–9.5
COEF	BRIGADE	TANK AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	TA_TANK	SUM	52.6		29.2	
PIPE	BRIGADE	OA_TANK	READY	0.	–9.4	0.	–9.4
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	OA_T/APC	SUM	12.0		5.45	
PIPE	BRIGADE	OA_APC	READY	0.	–9.4	0.	–9.4
FROM	BRIGADE	OTHR AMM	WEAPON	16.8		7.56	
COEF	BRIGADE	OA_T/APC	SUM	16.8		7.56	

The two new constraints are defined and their right-hand sides are initialized to zero. Next, tanks and APCs compete for weapon crews (the two activities with priority –10). For each tank with enough crew members to engage, the BRIGADE .. TOT_TANK .. READY activity adds 52.6 units to the right-hand side of the Blue BRIGADE .. TA_TANK .. SUM constraint and 12.0 units to the right-hand side of the Blue BRIGADE .. OA_T/APC .. SUM constraint. The BRIGADE .. TOT_APC .. READY activity also adds to the right-hand side of the BRIGADE .. OA_T/APC SUM constraint.

The BRIGADE .. TA_TANK .. READY activity rate is determined next. At this point, the right-hand side of the BRIGADE .. TA_TANK .. SUM constraint is equal to the amount of tank ammunition required to give a full load of ammunition to all tanks with crews. The right-hand side of BRIGADE .. TANK AMM .. WEAPON is, of course, the total tank ammunition available. The BRIGADE .. TA_TANK .. READY activity will be made equal to the number of tanks that could engage with a full load of tank ammunition. Of course, if this number is less than the number of tanks with enough crew members to engage, the ammunition would be shared among the tanks. No tank would engage with zero tank ammunition; likewise, no tank would engage with a full load.

Finally, LDM will simultaneously calculate rates for the BRIGADE .. OA_TANK .. READY and BRIGADE .. OA_APC .. READY activities. In these activities, the tanks and APCs with sufficient crews compete for other ammunition. At this point, the right-hand side of BRIGADE .. OA_T/APC .. SUM is equal to the amount of other ammunition needed to provide full loads to all tanks and APCs that can be crewed. If the amount of other ammunition available is smaller than this, tanks and APCs will engage with only partial loads of other ammunition. The BRIGADE .. OA_TANK .. READY and BRIGADE .. OA_

APC .. READY activities will be set to the numbers of tanks and APCs that could engage with full loads of other ammunition.

Changes to the ATTRITION Functions

These changes to the SUPPORT files should be accompanied by changes to the ATTRITION functions. Instead of a single TANK weapon, there are three: namely, TOT_TANK, TA_TANK, and OA_TANK. We would give the TOT_TANK weapon the attrition function of the original, single tank weapon; we would give the other two tank weapons zero attrition. (TOT_TANK is the total number of tanks engaged, so attriting the other two would be double counting.) Similarly, there are two APC weapons: namely, TOT_APC and OA_APC. TOT_APC would have the original attrition function, while OA_APC would have zero attrition.

Combat Worth Coefficients

We would calculate the combat worth coefficients for the three types of tanks as follows. (APC combat worths would be determined similarly.) Assume that the combat worth of a tank is a linear function of the fractions it carries of full loads of tank and other ammunition. That is, if:

υ = fraction of full "tank ammunition" load; and

ϕ = fraction of full "other ammunition" load;

then the combat worth for the average tank is:

$$CW = a_0 + a_1\upsilon + a_2\phi \tag{4.1}$$

where the coefficients a_0, a_1, and a_2 of this linear function have yet to be determined. The fractions can be calculated in terms of the three tank weapons, as follows:

$$\upsilon = \frac{TA\_TANK}{TOT\_TANK} \tag{4.2a}$$

$$\phi = \frac{OA\_TANK}{TOT\_TANK} \tag{4.2b}$$

If we substitute, the combat worth for an average tank is:

$$CW = a_0 + a_1 \times \frac{TA\_TANK}{TOT\_TANK} + a_2 \times \frac{OA\_TANK}{TOT\_TANK} \tag{4.3}$$

Or, multiplying by TOT_TANK (which equals total engaged tanks), the total combat worth of tanks is:

$$TCW = a_0 TOT\_TANK + a_1 TA\_TANK + a_2 OA\_TANK \tag{4.4}$$

That is, a_0, a_1, and a_2 are the combat worth coefficients of TOT_TANK, TA_TANK, and OA_TANK, respectively.

However, it may be difficult to obtain values for a_0, a_1, and a_2. One possibility is that a tank has the same combat worth, regardless of how much or how little ammunition it carries. This implies that a_1 and a_2 are zero, and only a_0 has a positive value. This possibility is ridiculous if taken to extremes, for a tank with no ammunition can have at most a fleeting psychological value. But if one expects that there will always be enough ammunition to provide nearly full loads (e.g., 75 percent or more), this approximation may be a good one.

Another possibility is that a tank has no combat worth without ammunition. One might ascribe, say, 90 percent of its worth to the tank ammunition, and 10 percent to other ammunition. Then a_0 will be zero, while a_1 and a_2 will be 90 percent and 10 percent, respectively, of the combat worth of a fully loaded tank.

Coefficients in Combat Loss Functions

We would give both TOT_TANK and OA_TANK zero coefficients in the CBT_LOSS function for tank ammunition consumption, thus relating all consumption of tank ammunition to the TA_TANK weapon. Similarly, both TOT_TANK and TA_TANK would have zero coefficients in the CBT_LOSS function for other ammunition consumption. All other CBT_LOSS coefficients—for example, for tanks K-Killed, or weapon crew wounded—would be coefficients of TOT_TANK, and the coefficients of TA_TANK and OA_TANK would be zero.

OA_APC has a coefficient in the CBT_LOSS function for other ammunition consumption, while TOT_APC has a zero coefficient. In all other CBT_LOSS functions involving APCs, TOT_APC has the coefficient and OA_APC is zero.

PREFERRED VERSUS NONPREFERRED MUNITIONS

Suppose that tanks can use one of two kinds of munitions: a preferred kind (called NEW_AMM) and an old, less effective kind (called OLD_AMM). At the start of hostilities, and as long as the preferred munitions are available, one wants tanks to use them. But when the preferred munition is exhausted, tanks will fight with the old munition.

If we ignore the fact that we want tanks to share the resource WPN CREW with APCs, we need only define two variations on the tank weapon: one using the preferred munition, and the other using the old munition. The version using the preferred munition will have a higher priority. The records in the SUPPORT file would look like this:

PIPE	BRIGADE	TANK	READY	0.	–10.	0.	–10.
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	NEW_AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	4.0		4.0	
PIPE	BRIGADE	TANK	READY	0.	–9.5	0.	–9.5
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	OLD_AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	4.0		4.0	

However, we want tanks to share the WPN CREW resource with APCs. If we have a single APC weapon variant, it cannot have the same priority as both variants of the tank weapon. If its priority is the same as the preferred munition variant of the tank weapon, as soon as NEW_AMM runs out, the APC weapons will claim as many WPN CREW as they need, before any of the old munition variant of the tank weapon receives any WPN CREW. Similarly, if the APC weapon has the same priority as the old munition tank variant, it will not begin to share WPN CREW until all the NEW_AMM is exhausted.

The solution is to define two APC variants. They will be identical except that each will share the priority of one of the tank variants, and each will require a token amount of either NEW_AMM or OLD_AMM. The SUPPORT records needed are as follows:

PIPE	BRIGADE	TANK_NEW	READY	0.	–10.	0.	–10.
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	NEW_AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	4.0		4.0	
PIPE	BRIGADE	APC_NEW	READY	0.	–10.	0.	–10.
FROM	BRIGADE	APC	WEAPON	1.		1.	
FROM	BRIGADE	OTHR AMM	WEAPON	16.8		7.56	
FROM	BRIGADE	WPN CREW	WEAPON	4.		4.	
FROM	BRIGADE	NEW_AMM	WEAPON	0.01		0.01	
PIPE	BRIGADE	TANK_OLD	READY	0.	–9.5	0.	–9.5
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	OLD_AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	4.0		4.0	

PIPE	BRIGADE	APC_OLD	READY	0.	–9.5	0.	–9.5
FROM	BRIGADE	APC	WEAPON	1.		1.	
FROM	BRIGADE	OTHR AMM	WEAPON	16.8		7.56	
FROM	BRIGADE	WPN CREW	WEAPON	4.		4.	
FROM	BRIGADE	OLD_AMM	WEAPON	0.01		0.01	

With these weapon preparation activities in place, as long as any NEW_AMM remains, the first two variants of both the tank and APC weapons will have first call on all other resources, and will share WPN CREW between themselves. Once NEW_AMM runs out, none of the NEW_AMM variants of the tank or APC weapon can be formed, and the OLD_AMM variants will employ the necessary resources as though there were only one variant of each.

As far as LDM is concerned, each variant of a weapon is a weapon in its own right. It can have a different combat worth coefficient and attrition table in the ATTRITION file. The new munition can have different CBT_LOSS data than the old. In particular, it is possible to make the tank with the preferred munition more effective than the tank with the old munition, and to make the consumption of the new munition lower per engaged tank than the consumption of the old munition. On the other hand, it is not necessary for variants of a weapon to have different combat worths or different attrition tables. In the example, the two APC variants are not really different; they would have identical data in the ATTRITION file.

DIFFERENCES BETWEEN BLUE AND RED WEAPONS

The ATTRITION and SUPPORT files require that Blue and Red have the same weapons and the same support activities to prepare them for battle (albeit the two sides' weapons can have different values for their various parameters). Thus, if Blue has two tank variants, so must Red. However, the user can arrange for the number of one of the variants to be zero for Red; in effect, this leaves Red with only the other variant.

In the example using preferred and nonpreferred munitions, one can restrict Red to only the nonpreferred variant by never supplying Red with any of the NEW_AMM resource. LDM will still calculate rates for Red's TANK_NEW and APC_NEW activities, but the rates will always be zero.

In the example using partial crews, suppose that Red tanks must always have crews of four. To ensure this result, we change the Red crew size in the BRIGADE .. TOT_TANK .. DUMMY activity from three to four, and we alter the BRIGADE .. TANK4 .. READY activity so that it no longer adds an extra member to the Red crew. The resulting records are as follows:

CONSTR	BRIGADE	TOT_TANK	SUM				
PIPE	BRIGADE	TOT_TANK	DUMMY	0.	–10.	0.	–10.
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	TANK AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	3.0		4.0	
COEF	BRIGADE	TOT_TANK	SUM	–1.0		–1.0	
PIPE	BRIGADE	APC	READY	0.	–10.	0.	–10.
FROM	BRIGADE	APC	WEAPON	1.		1.	
FROM	BRIGADE	OTHR AMM	WEAPON	16.8		7.56	
FROM	BRIGADE	WPN CREW	WEAPON	4.		4.	
PIPE	BRIGADE	TANK4	READY	0.	–9.5	0.	–9.5
COEF	BRIGADE	WPN CREW	WEAPON	1.0		0.0	
COEF	BRIGADE	TOT_TANK	SUM	1.0		1.0	
PIPE	BRIGADE	TANK3	READY	0.	–9.4	0.	-9.4
COEF	BRIGADE	TOT_TANK	SUM	1.0		1.0	

With these changes, LDM will put a crew of four in every Red tank. The Red BRIGADE .. TOT_TANK .. DUMMY activity rate will be calculated just as the old Red BRIGADE .. TANK .. READY activity rate was, and with the same result. Then Red's BRIGADE .. TANK4 .. READY will be set equal to Red's BRIGADE .. TOT_TANK .. DUMMY, and Red's BRIGADE .. TANK3 .. READY will be set to zero.

5. THE AMMUNITION DISTRIBUTION FUNCTION

LDM is distributed with a test case that contains one formulation of the ammunition distribution function (see [3], Chapter 8). This section presents an alternate formulation of the same function. Before the reader begins this section, we recommend that he review Chapter 5 of the LDM Users' Manual [3], which describes the different types of records in a SUPPORT file and explains their formats and data elements.

The formulation in this section differs from the test case in two major ways. First, the test case had only one path by which ammunition could be delivered to the BRIGADE echelon, where it is consumed. Here, ammunition can be distributed through a network containing multiple paths; it is necessary to establish how ammunition flows are to be distributed among them. Second, in the test case, constraints on the capacity to distribute ammunition are expressed in terms of specific resources, such as trucks and drivers. Here, capacities are expressed directly as capacities (e.g., tons/day of ammunition handling capacity, or ton-km/day of transportation capacity). The capacities must be estimated outside LDM, by models that relate the capacities to resources, as described in [2].

This formulation relies on models outside LDM. This is a departure from the very common approach to modeling that seeks to include all factors in a single, large model. As outlined in Section 1, we designed the POLA methodology as a suite of smaller models, each of which can be exercised individually, but all of which can be used together in a single, integrated analysis (see Fig. 1.1). We view LDM as a central tool in such an analysis, a tool that can incorporate and integrate the results from other models. This section gives an example of how results from one kind of model can be incorporated in LDM.

THE AMMUNITION DISTRIBUTION NETWORK

Figure 5.1 shows the doctrinal network for ammunition distribution, as described in Field Manual FM 9-6 [7]. The tasks required to distribute ammunition are transporting ammunition along each link and handling it at each node. The nodes are the port, the Theater Storage Area (TSA), the Corps Storage Area (CSA), the Ammunition Supply Point (ASP), and the Ammunition Transfer Point (ATP). Handling involves loading and unloading ammunition from trains or trucks, warehousing it temporarily, sorting and consolidating it by type of ammunition, and so on.

The only mode of transport we consider is truck transport. In NATO, the U.S. Army plans that much of the ammunition moved from ports and TSAs will move by rail. We could have added links to Fig. 5.1 to represent rail transport, but for simplicity we have ignored it.

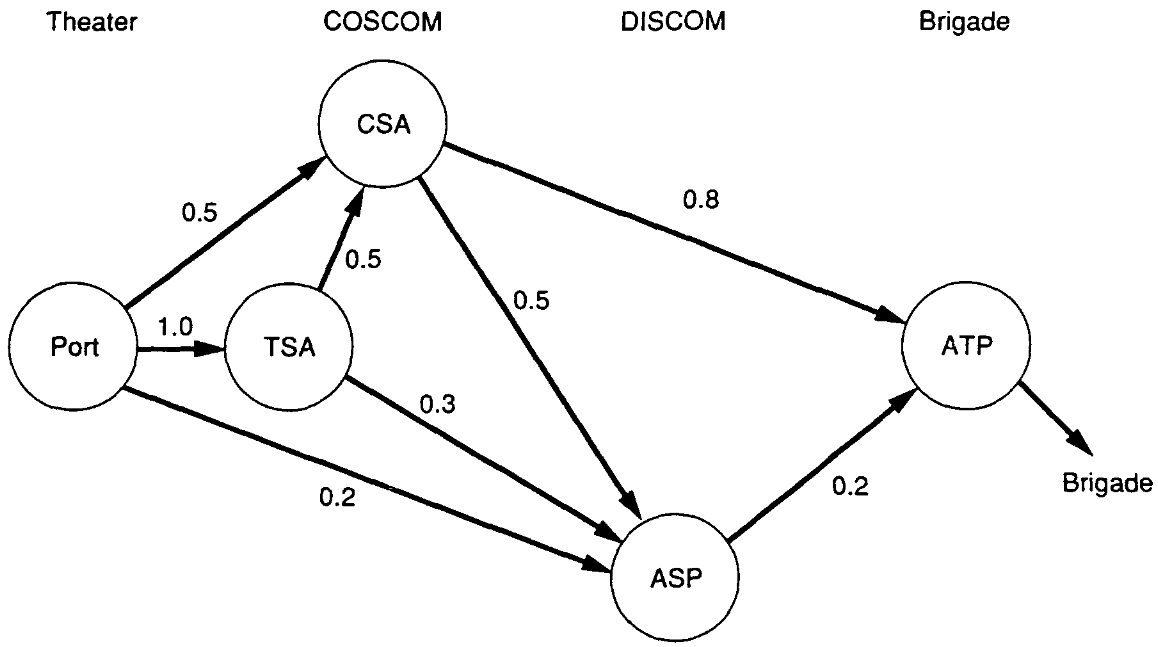

Fig. 5.1—Ammunition Distribution Network

The fractions shown on the figure dictate how much of the demand for ammunition at each node is requisitioned from each of the other nodes. For example, 80 percent of the demand at the ATP is requisitioned from the CSA, bypassing the ASP.

In our example formulation of the ammunition distribution function, each activity corresponds to transporting one type of ammunition along one of the links in Fig. 5.1. If LDM considers four ammunition types—artillery, Multiple Launch Rocket System (MLRS), tank, and other—then to each link will correspond four activities: one activity that transports artillery ammunition, another MLRS ammunition, a third tank ammunition, and the fourth other ammunition. Table 5.1 lists the names of the nine activities in our example formulation that correspond to the distribution of tank ammunition, as the activities would appear in the SUPPORT files. These activities would be replicated for each of the other ammunition types. It should be evident from the names which activity corresponds to which link.

Three constraints play a direct role in the distribution of ammunition. First, ammunition *balance* or *inventory* constraints prevent LDM from issuing more ammunition from a node than is available. Second, *capacity* constraints prevent more ammunition from being handled at any node, or transported along any link, than there is capacity to

Table 5.1

Activities for Distributing Tank Ammunition

PORT-TSA	TANK AMM	RESUPPLY
PORT-CSA	TANK AMM	RESUPPLY
PORT-ASP	TANK AMM	RESUPPLY
TSA-CSA	TANK AMM	RESUPPLY
TSA-ASP	TANK AMM	RESUPPLY
CSA-ASP	TANK AMM	RESUPPLY
CSA-ATP	TANK AMM	RESUPPLY
ASP-ATP	TANK AMM	RESUPPLY
ATP-BDE	TANK AMM	RESUPPLY

accommodate. Third, *requisition* constraints prevent a node from requisitioning more ammunition of any type than the quantity that will raise its stock on hand to the authorized level. These constraints also limit the amounts of requisitioned ammunition that can be transported along each link. In the following sections, we address each of these constraints in turn.

BALANCE CONSTRAINTS AND DURATIONS OF ACTIVITIES

The balance (or inventory) constraints prevent more of any type of ammunition from being issued by a node than there is ammunition available. These constraints are implemented in the SUPPORT files by means of FROM and TO records (see [3], Chapter 5, and Appendix B of this Note). There is one balance constraint at each node for each type of ammunition. Each activity contributes one term to each of two balance constraints: the first to a constraint for the node *from* which the activity takes ammunition, and the second to a constraint for the node *to* which the activity delivers ammunition.

The term in the constraint for the node *to* which the activity delivers ammunition is of particular interest. LDM simulates the time required to perform an activity (in this instance, a transportation time) by allowing some of the ammunition to arrive at its destination during the same time period as it departed from its destination, and by delaying the arrival of the rest of the ammunition until subsequent time periods. By adjusting the fraction of the ammunition delayed by zero, one, two, or more time periods, the user can make the average transportation time whatever he wishes. The user specifies the desired average transportation time, and LDM calculates these fractions automatically, when it encounters a TO record in a SUPPORT file (see [3], Chapter 5). The formulas it uses, and the rationale behind them, are described in Appendix B.

To calculate the durations for these activities, we must know the lengths of the different links in Fig. 5.1, the transport velocities along those links, and the delay times for loading, unloading, and so on. Table 5.2 gives illustrative link lengths in kilometers from Field Manual FM 9-6. According to Field Manual FM 55-15 [8], trucks traveling to the rear of the CSA will have an average velocity of 32 km/hr, while those traveling closer to the front than the CSA will have an average velocity of 16 km/hr. Links of Fig. 5.1 that lie entirely behind the CSA will have higher velocity, while links entirely forward of the CSA will have lower velocity. Links that are partly behind and partly forward of the CSA will have the appropriate velocity on each part—hence, an average velocity between 16 and 32 km/hr.

Loading and unloading delays are as follows. Trailers loaded at the PORT or the TSA will be the 40-foot trailer characteristic of the truck companies that operate behind the Corps rear boundary; they will require 4 hours loading time, and another 4 hours for unloading at their destination. Trailers loaded at the CSA or ASP will be the smaller, 20-foot trailers characteristic of the companies operating farther forward; they will require 3 hours for loading. They will also require 3 hours for unloading at the ASP, but 5 hours if unloaded at the ATP. The longer time at the ATP includes time needed for trucks belonging to combat units to bring the ammunition to the actual combat vehicles.

The other source of delay is caused by the transfer of trailers from one tractor to another at an intermediate point along a link. Truck companies operate like a bucket brigade. Each company moves loaded trailers from one end of a limited (no more than 144 kilometers long) stretch of road to the other, and (usually) empty trailers in the opposite direction. A trailer transfer point (TTP) occupies the meeting place of two adjacent stretches, where one truck company passes trailers along to the next. Links in Table 5.2 that are longer than 144 kilometers must be broken by TTPs [8]. Therefore, the number of TTPs on a link is one less than the number of 144-kilometer segments needed to cover that link. Table 5.3 lists the number of TTPs for each link of the ammunition distribution network, derived

Table 5.2

Illustrative Link Lengths (kilometers)

	To Node				
From Node	BDE	ATP	ASP	CSA	TSA
PORT	—	—	460	350	100
TSA	—	—	360	250	—
CSA	—	130	110	—	
ASP	—	20	—		
ATP	10	—			

Table 5.3

Trailer Transfer Points per Link

	To Node				
From Node	BDE	ATP	ASP	CSA	TSA
PORT	—	—	3	2	0
TSA	—	—	2	1	—
CSA	—	0	0	—	
ASP	—	0	—		
ATP	0	—			

from Table 5.2 by this procedure. We assume that each trailer transfer causes a delay of 1 hour.

The durations of the ammunition distribution activities consist of a time to load the ammunition at the origin, a travel time, delays at TTPs, and a time to unload the ammunition at the destination. For example, transporting ammunition from the PORT to the CSA requires 4 hours each for loading and unloading, plus 10.9375 hours of actual travel time (350 km at 32 km/hr), plus transfers at two TTPs costing 1 hour apiece. The total duration for this activity is 20.94 hours. Durations for the other activities can be calculated similarly, and appear in Table 5.4. The ATP-BDE activity is a special case. Combat units (brigades) send their own trucks to the ATP to pick up ammunition. Their trucks are relatively small, and we assume the loading plus unloading time is negligible. The user may substitute his own numbers for this or any other entry in Table 5.4.

CAPACITY CONSTRAINTS

Identification of Capacity Constraints

Army doctrine assigns each ammunition distribution task to a type of Combat Service Support (CSS) unit. Tables 5.5 and 5.6 list the respective nodes and links of the ammunition distribution network, and the kinds of CSS units that perform the tasks associated with them, as gleaned from [7, 9, 10]. Each CSS unit may exist in several versions; each version is identified by its own Standard Requirements Code (SRC). The SRCs, which are also listed in the tables, identify the Tables of Organization and Equipment (TOEs) that describe units of that type in detail.

In our example formulation of the ammunition distribution function, we will define a capacity constraint for each type of unit shown in Tables 5.5 and 5.6.[1] We define no constraint for ammunition handling at either the ATP or the PORT; we assume that there is

[1]It might be more natural to express capacities to perform the various support activities in terms of logistics resources, such as trucks and drivers. However, many resources may influence the

Table 5.4

Durations of Ammunition Distribution Activities

	At 32 km/hr		At 16 km/hr		Load	TTP	Total
Activity	Dist	Time	Dist	Time	+Unload	Delay	Duration
PORT-TSA	100	3.125			4+4		11.13
PORT-CSA	350	10.9375			4+4	2	20.94
PORT-ASP	350	10.9375	110	6.875	4+4	3	28.81
TSA-CSA	250	7.8125			4+4	1	16.81
TSA-ASP	250	7.8125	110	6.875	4+4	2	24.69
CSA-ASP			110	6.875	3+3		12.88
CSA-ATP			130	8.125	3+5		16.13
ASP-ATP			20	1.25	3+5		9.25
ATP-BDE			10	0.625			0.63

Table 5.5

Ammunition Handling Tasks and Units

Node	Unit Nomenclature	SRC
ATP	(Team from DISCOM)	—
ASP	DS Ordnance Co.	09064H100 09487L000
CSA TSA	GS Ordnance Co.	09074H100 09488L000
PORT	(Local Citizens)	—

Table 5.6

Ammunition Transport Tasks and Units

Link	Unit Nomenclature	SRC
ATP-U.S.ER	(Using unit)	—
ASP-ATP, CSA-(any)	Corps TMT Co.	55023J410 55728L100
TSA-(any), PORT-(any)	Theater TMT Co.	55018J410 55727L100
(long links)	Trailer Transfer Point	55540H5GE 55540LE00

always ample capacity to perform these tasks. There will be a single constraint for all GS Ordnance Companies, without distinguishing those at the TSA from those at the CSA. This

capacity to perform a support activity, and it is impractical to include more than a few in LDM, lest the simulation become too large and complex. Therefore, we estimate the capacities of CSS units in models outside LDM (see [2]). Inside LDM, each kind of capacity is represented by a single constraint.

is tantamount to assuming that GS Ordnance Companies can be moved rapidly within the theater to provide capacity at whichever node it is needed. The other four capacity constraints correspond to the tasks done by DS Ordnance Companies, Corps TMT Companies, Theater TMT Companies, and Trailer Transfer Points, respectively.

Calculation of Capacities

The capacity available to perform a given task will appear in LDM as the right-hand side of a capacity constraint. At any time in the simulation, it should equal the total capacity of all units available to perform that task at that time. The companion report [2] describes a way to calculate the capacity; but we briefly outline the method here.

First, we list the specific units, by UIC,[2] that will provide the capacity, and the time at which each of the units will appear in the theater, ready to go to work. We then calculate each unit's capacity. Finally, the TIME_PHASE file specifies each increment of capacity that enters the simulated theater.

There are two steps in calculating a unit's capacity. First, we identify each unit's design capacity. The design capacity of a unit is a characteristic of its SRC (i.e., different units with the same SRC have the same design capacity). We obtain most design capacities from the narrative portions of TOEs, or from the field manuals that describe units of different types. Or, we can inquire of the TRADOC school responsible for the SRC. Second, we adjust the design capacity to reflect any shortages of equipment.

When a user performs an analysis, he will define several analysis cases. Ordinarily, there should be a *base case*, which reflects the units and their equipment that the Army currently plans to deploy to the theater being analyzed. There should also be one or more *excursion cases*, in which something is changed from its value in the base case. One kind of change the POLA methodology is intended to analyze is the addition of equipment to units that currently have shortages. To construct an excursion case in which some equipment shortages have been remedied, we add equipment to units that have shortages, and then we readjust their design capacities.

Calculation of Workloads

Each activity in Table 5.1 involves handling tasks at both the origin and destination nodes, and transport tasks on the link. For example, the activities for the link from TSA to

[2]Until this point, we have discussed only unit types, designated by SRC codes. Each specific unit also has a *unit identification code* (UIC). With this code, we can access a number of standard Army data files to learn about the specific unit. For example, from the TAEDP (Total Army Equipment Distribution Program), we can learn what items of equipment the unit possesses; from the FAS (Force Accounting System), we can learn the "latest arrival date" of that unit in its assigned theater.

CSA consist of half of the handling task at the TSA (either receiving or issuing ammunition), plus transportation from the TSA to the CSA, plus half of the handling task at the CSA. This link is long enough to require a trailer transfer point, so the activity also includes the link's trailer transfer tasks.

We now work out how much workload for each type of CSS unit will be generated by each activity, in turn. We express each activity rate in hundreds of pounds of ammunition moved per 12-hour period (this is written as Hlb/12Hr). The *DS Ordnance Company* handles ammunition at the ASP, so the activities that generate workload for this type of unit are the activities that move ammunition either to the ASP or from the ASP. These activities correspond to the links PORT-ASP, TSA-ASP, CSA-ASP, and ASP-ATP in Fig. 5.1. The capacity of a DS Ordnance Company is expressed in tons/day of ammunition handled; handling a ton of ammunition means both receiving it when it arrives at the ASP *plus* issuing it when it departs. Each activity performs only half of the handling task at the ASP—i.e., either receiving or issuing. Thus, for each Hlb/12Hr of ammunition received (or issued) at the ASP, DS Ordnance Companies will face a workload of 0.5 Hlb/12Hr, or (converting units) 0.05 ton/day.

The *GS Ordnance Company* handles ammunition at both the TSA and the CSA, so the activities that generate workload for this type of unit are those that correspond to the links PORT-TSA, PORT-CSA, TSA-CSA, TSA-ASP, CSA-ASP, and CSA-ATP. The same calculations apply here as for the DS Ordnance Company, with one exception. The TSA-CSA activity involves both issuing ammunition from the TSA and receiving it at the CSA. Hence, this activity generates 0.1 ton/day workload for GS Ordnance Companies for each Hlb/12Hr of ammunition moved, while the other activities generate only 0.05 ton/day workload per Hlb/12Hr.

Workloads for *TMT companies* are expressed as ton-kilometers per day. Thus, to calculate the workload an activity generates for a TMT company, we use the link lengths from Table 5.2. According to Table 5.6, workloads for Corps TMT companies are generated by the activities for the links ASP-ATP, CSA-ATP, and CSA-ASP. Similarly, Theater TMT Companies receive their workload from the activities for links TSA-ASP, TSA-CSA, PORT-ASP, PORT-CSA, and PORT-TSA. Each Hlb/12Hr of ammunition transported equals 0.1 ton/day; this can be multiplied by the link lengths to determine the workloads in ton-km/day.

The workload of a *TTP* is expressed as the number of trailers it must process; processing includes the receipt of a trailer plus the issuance of one. To estimate the TTP workload generated by an activity, we must calculate the fraction of a trailer per day needed to transport each Hlb/12Hr of ammunition, and then multiply by the number of TTPs on the

associated link (see Table 5.3). We must multiply by another factor of two, because each trailer must be ɔcessed through a TTP twice—once when it is carrying ammunition forward, and a second time when it returns empty.

The Theater TMT Company uses a 40-foot trailer with a maximum load of 34 tons, and an average load of 22 tons (figures from FM 55-15).[3] Moving one Hlb/12Hr will generate a flow of 0.1/22, or 0.00455, 40-foot trailers per day. As an example, to calculate the TTP workload generated by each Hlb/12Hr PORT-ASP activity, we multiply 0.00455 trailers/day by the number of TTPs on that link (three, from Table 5.3) and again by two. The result is 6×0.00455, or 0.0273.

Tabie 5.7 shows all the coefficients for generating CSS unit workloads for the ammunition distribution function.

REQUISITION CONSTRAINTS

To ensure that ammunition flows are distribu⁺ :ording to the specified distribution fractions, one must introduce a requisition constraint for each link. Each constraint will prohibit more than a specified quantity of the ammunition requisitioned by a node from being supplied via that link.

The user specifies how much ammunition each node is authorized. In each time period, that node has a local need for enough ammunition to fill its stocks on hand to the authorized quantity, less the amount already due in. In addition, the node needs enough more ammunition to satisfy requisitions from nodes further forward in the ammunition distribution network. We calculate the local need at node "i" as follows. Let:

Table 5.7

CSS Unit Workloads Generated by Each Ammunition Distribution Activity

Activity (Hlb/12Hr)	DS Ord (tons/day)	GS Ord (tons/day)	Corps TMT ton-km/day)	Theater TMT (ton-km/day)	TTP (trls/day)
PORT-TSA	—	0.05	—	10.	—
PORT-CSA	—	0.05	—	35.	0.0182
PORT-ASP	0.05	—	—	46.	0.0273
TSA-CSA	—	0.1	—	25.	0.0091
TSA-ASP	0.05	0.05	—	36.	0.0182
CSA-ASP	0.05	0.05	11.	—	—
CSA-ATP	—	0.05	13.	—	—
ASP-ATP	0.05	—	2.	—	—
ATP-BDE	—	—	—	—	—

[3]There are no TTPs on links served by Corps TMT Companies, so similar data for this unit are not necessary. For the sake of completeness, however, the Corps TMT Company uses a 20-foot trailer with a maximum load of 22.5 tons and an average load of 15 tons.

$L_i(P)$ = local need for ammunition at node "i" during period "P."

$AUTH_i$ = amount of ammunition node "i" is authorized.

$OH_i(P)$ = amount of ammunition on hand at node "i" at the start of period "P."

$DI_i(P)$ = amount of ammunition due in to node "i" as of the start of period "P."

Then:

$$L_i(P) = AUTH_i - OH_i(P) - DI_i(P) \tag{5.1}$$

The total amount requisitioned by a node is the local need at the node plus the amount requisitioned from that node by other nodes. Let:

$RQ_i(P)$ = total amount requisitioned by node "i" during period "P."

$r_{ij}(P)$ = amount requisitioned from node "i" by node "j" during period "P."

Then:

$$RQ_i(P) = L_i(P) + \sum_j r_{ij}(P) \tag{5.2}$$

Finally, the distribution fractions from Fig. 5.1 dictate how much of the total requisition will come from each of the nodes that can supply node "i." Let:

δ_{ij} = fraction of the total requisition by node "j" that comes from node "i."

The fractions for our example are shown in Table 5.8. (They are the same as the distribution fractions that appear on the links of Fig. 5.1.)[4]

Then:

$$r_{ij}(P) = \delta_{ij} \times RQ_j(P) \tag{5.3}$$

[4]A user may specify different fractions for different ammunition types. For example, one might wish to require that 100 percent of artillery ammunition deliveries to the ATP come directly from the CSA while requiring 100 percent of other ammunition come from the ASP.

Table 5.8

Distribution Fractions

	To Node				
From Node	BDE	ATP	ASP	CSA	TSA
PORT	—	—	0.2	0.5	1.0
TSA	—	—	0.3	0.5	—
CSA	—	0.8	0.5	—	
ASP	—	0.2	—		
ATP	1.0	—			

The quantity $r_{ij}(P)$ will serve as the upper bound on the amount of ammunition that may be transported on the link from node "i" to node "j" during period "P." It will be convenient to substitute Equation (5.3) into Equation (5.2), and use the resulting equation, labeled (5.4), in place of Equation (5.2).

$$RQ_i(P) - \sum_j \delta_{ij} RQ_j(P) = L_i(P) \tag{5.4}$$

IMPLEMENTING THE AMMUNITION DISTRIBUTION FUNCTION IN LDM

The Requisition Constraints

To implement the example formulation of the ammunition distribution function in LDM, we must prepare the appropriate records for the SUPPORT files. The following records implement Equation (5.1) for tank ammunition at every node except the port. They should be replicated for the other types of ammunition.[5]

CONSTR	BRIGADE	TANK AMM	LOC NEED		
RHS	BRIGADE	TANK AMM	AUTH	1.0	1.0
RHS	BRIGADE	TANK AMM	ON HAND	–1.0	–1.0
RHS	ATP-BDE	TANK AMM	RESUPPLY	–1.0	–1.0
CONSTR	ATP	TANK AMM	LOC NEED		
RHS	ATP	TANK AMM	AUTH	1.0	1.0
RHS	ATP	TANK AMM	ON HAND	–1.0	–1.0
RHS	CSA-ATP	TANK AMM	RESUPPLY	–1.0	–1.0
RHS	ASP-ATP	TANK AMM	RESUPPLY	–1.0	–1.0
CONSTR	ASP	TANK AMM	LOC NEED		
RHS	ASP	TANK AMM	AUTH	1.0	1.0

[5]As before, each CONSTR record defines a resource (in this case a local need for ammunition) and the consequent authority to requisition it. (This illustrates how broadly one may construe the notion of "resource," to mean anything whose lack may constrain one's activities.) The RHS records that follow a CONSTR record define how to calculate the quantity of the local need resource in terms of quantities of other resources—in this case an authorized quantity, a quantity on hand, and a quantity due in.

RHS	ASP	TANK AMM	ON HAND	–1.0	–1.0
RHS	PORT-ASP	TANK AMM	RESUPPLY	–1.0	–1.0
RHS	TSA-ASP	TANK AMM	RESUPPLY	–1.0	–1.0
RHS	CSA-ASP	TANK AMM	RESUPPLY	–1.0	–1.0
CONSTR	CSA	TANK AMM	LOC NEED		
RHS	CSA	TANK AMM	AUTH	1.0	1.0
RHS	CSA	TANK AMM	ON HAND	–1.0	–1.0
RHS	PORT-CSA	TANK AMM	RESUPPLY	–1.0	–1.0
RHS	TSA-CSA	TANK AMM	RESUPPLY	–1.0	1.0
CONSTR	TSA	TANK AMM	LOC NEED		
RHS	TSA	TANK AMM	AUTH	1.0	1.0
RHS	TSA	TANK AMM	ON HAND	–1.0	–1.0
RHS	PORT-TSA	TANK AMM	RESUPPLY	–1.0	–1.0

The port will keep as much ammunition as is not requisitioned by another node, so it is not necessary to define a local need for this node. The records naming resources with the same names as the ammunition distribution activities from Table 5.1 represent the quantities of ammunition in transit as of the start of a time period. These are, therefore, the "due in" quantities from Equation (5.1).

Next, we define activities that implement Equations (5.3) and (5.4). There will be one activity for each node "i" that requisitions ammunition; the activity will be defined so that LDM will calculate its value to be $RQ_i(P)$. These activities will calculate the right-hand sides of constraints on the amount of ammunition that can be transported on each link. We initialize the right-hand sides of those constraints to zero with the following SUPPORT records. These records should be replicated for the other types of ammunition.

CONSTR	ATP-BDE	TANK AMM	RQUISITN
CONSTR	ASP-ATP	TANK AMM	RQUISITN
CONSTR	CSA-ATP	TANK AMM	RQUISITN
CONSTR	CSA-ASP	TANK AMM	RQUISITN
CONSTR	TSA-ASP	TANK AMM	RQUISITN
CONSTR	PORT-ASP	TANK AMM	RQUISITN
CONSTR	TSA-CSA	TANK AMM	RQUISITN
CONSTR	PORT-CSA	TANK AMM	RQUISITN
CONSTR	PORT-TSA	TANK AMM	RQUISITN

The activities that calculate the right-hand sides of the constraints are as follows:

PIPE	BRIGADE	TANK AMM	RHSCAL	0.	–20.	0.	–20.
COEF	BRIGADE	TANK AMM	LOC NEED	1.0		1.0	
COEF	ATP	TANK AMM	LOC NEED	–1.0		–1.0	
COEF	ATP-BDE	TANK AMM	RQUISITN	–1.0		–1.0	

PIPE	ATP	TANK AMM	RHSCAL	0.	–19.	0.	–19.
COEF	ATP	TANK AMM	LOC NEED	1.0		1.0	
COEF	ASP	TANK AMM	LOC NEED	–0.2		–0.2	
COEF	CSA	TANK AMM	LOC NEED	–0.8		–0.8	
COEF	ASP-ATP	TANK AMM	RQUISITN	–0.2		–0.2	
COEF	CSA-ATP	TANK AMM	RQUISITN	–0.8		–0.8	
PIPE	ASP	TANK AMM	RHSCAL	0.	–18.	0.	–18.
COEF	ASP	TANK AMM	LOC NEED	1.0		1.0	
COEF	CSA	TANK AMM	LOC NEED	–0.5		–0.5	
COEF	TSA	TANK AMM	LOC NEED	–0.3		–0.3	
COEF	CSA-ASP	TANK AMM	RQUISITN	–0.5		–0.5	
COEF	TSA-ASP	TANK AMM	RQUISITN	–0.3		–0.3	
COEF	PORT-ASP	TANK AMM	RQUISITN	–0.2		–0.2	
PIPE	CSA	TANK AMM	RHSCAL	0.	–17.	0.	–17.
COEF	CSA	TANK AMM	LOC NEED	1.0		1.0	
COEF	TSA	TANK AMM	LOC NEED	–0.5		–0.5	
COEF	TSA-CSA	TANK AMM	RQUISITN	–0.5		–0.5	
COEF	PORT-CSA	TANK AMM	RQUISITN	–0.5		–0.5	
PIPE	TSA	TANK AMM	RHSCAL	0.	–16.	0.	–16.
COEF	ATP	TANK AMM	LOC NEED	1.0		1.0	
COEF	PORT-TSA	TANK AMM	RQUISITN	–1.0		–1.0	

The coefficients in these records come from Table 5.8. The durations of these activities are zero, although a user might change this if he did not want requisitions to arrive at their destinations instantaneously. The priorities govern the order in which LDM calculates the activity rates, and they should *not* be changed. Once again, these records should be replicated for the other types of ammunition.

Right-Hand Sides for the Capacity Constraints

The capacity constraints must have right-hand sides, which we define with the following SUPPORT records.

CONSTR	ALL	GS ORD	CAP		
RHS	ALL	GS ORD	UNIT	1.	1.
CONSTR	ALL	DS ORD	CAP		
RHS	ALL	DS ORD	UNIT	1.	1.
CONSTR	ALL	THEA TMT	CAP		
RHS	ALL	THEA TMT	UNIT	1.	1.
CONSTR	ALL	CORP TMT	CAP		
RHS	ALL	CORP TMT	UNIT	1.	1.
CONSTR	ALL	TTP	CAP		
RHS	ALL	TTP	UNIT	1.	1.

Each of these constraints corresponds to a column in Table 5.7; it should be evident which constraint corresponds to which column. There is no need to replicate these records for other ammunition types, because a single capacity handles or transports all types of ammunition.

The available capacity of GS Ordnance Companies would appear as the right-hand side of the ALL .. GS ORD .. UNIT constraint, to which the user could from time to time specify additions by inserting the appropriate records in the TIME_PHASE file. The above SUPPORT records set the right-hand side of the ALL .. GS ORD .. CAP constraint equal to the right-hand side of the ALL .. GS ORD .. UNIT constraint. The ammunition resupply activities will deplete the ALL .. GS ORD .. CAP right-hand side, but they will not touch the right-hand side of the ALL .. GS ORD .. UNIT constraint. The latter constraint can be carried over to the next time period.

The Ammunition Resupply Activities

The ammunition distribution activities from Table 5.1 must be defined to have activity matrix coefficients in the balance constraints, capacity constraints, and requisition constraints described in the preceding sections.

The resupply activities are implemented by the following SUPPORT records. The balance constraints are implemented by the FROM and TO records. The capacity and requisition constraints are implemented by the COEF records. The coefficients in the capacity constraint records are from Table 5.7. The coefficients in the requisition constraint records all equal 1.0. These records should be replicated for the other types of ammunition.

PIPE	PORT-TSA	TANK AMM	RESUPPLY	11.13	15.3	0.	15.3
FROM	PORT	TANK AMM	ON HAND	1.0		1.0	
TO	TSA	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	GS ORD	CAP	0.05		0.	
COEF	ALL	THEA TMT	CAP	10.		0.	
PIPE	PORT-CSA	TANK AMM	RESUPPLY	20.94	15.2	0.	15.2
FROM	PORT	TANK AMM	ON HAND	1.0		1.0	
TO	CSA	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	GS ORD	CAP	0.05		0.	
COEF	ALL	THEA TMT	CAP	35.		0.	
COEF	ALL	TTP	CAP	0.0182		0.	
COEF	PORT-CSA	TANK AMM	RQUISITN	1.0		1.0	
PIPE	PORT-ASP	TANK AMM	RESUPPLY	28.81	15.1	0.	15.1
FROM	PORT	TANK AMM	ON HAND	1.0		1.0	
TO	ASP	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	DS ORD	CAP	0.05		0.	
COEF	ALL	THEA TMT	CAP	46.		0.	
COEF	ALL	TTP	CAP	0.0273		0.	
COEF	PORT-ASP	TANK AMM	RQUISITN	1.0		1.0	

PIPE	TSA-CSA	TANK AMM	RESUPPLY	16.81	15.5	0.	15.5
FROM	TSA	TANK AMM	ON HAND	1.0		1.0	
TO	CSA	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	GS ORD	CAP	0.1		0.	
COEF	ALL	THEA TMT	CAP	25.		0.	
COEF	ALL	TTP	CAP	0.0091		0.	
COEF	TSA-CSA	TANK AMM	RQUISITN	1.0		1.0	
PIPE	TSA-ASP	TANK AMM	RESUPPLY	24.69	15.4	0.	15.4
FROM	TSA	TANK AMM	ON HAND	1.0		1.0	
TO	ASP	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	GS ORD	CAP	0.05		0.	
COEF	ALL	DS ORD	CAP	0.05		0.	
COEF	ALL	THEA TMT	CAP	36.		0.	
COEF	ALL	TTP	CAP	0.0182		0.	
COEF	TSA-ASP	TANK AMM	RQUISITN	1.0		1.0	
PIPE	CSA-ASP	TANK AMM	RESUPPLY	12.88	15.7	0.	15.7
FROM	CSA	TANK AMM	ON HAND	1.0		1.0	
TO	ASP	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	GS ORD	CAP	0.05		?	
COEF	ALL	DS ORD	CAP	0.05		?	
COEF	ALL	CORP TMT	CAP	11.		?	
COEF	CSA-ASP	TANK AMM	RQUISITN	1.0		1.0	
PIPE	CSA-ATP	TANK AMM	RESUPPLY	16.13	15.6	0.	15.6
FROM	CSA	TANK AMM	ON HAND	1.0		1.0	
TO	ATP	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	GS ORD	CAP	0.05		0.	
COEF	ALL	CORP TMT	CAP	13.		0.	
COEF	CSA-ATP	TANK AMM	RQUISITN	1.0		1.0	
PIPE	ASP-ATP	TANK AMM	RESUPPLY	9.25	15.8	0.	15.8
FROM	ASP	TANK AMM	ON HAND	1.0		1.0	
TO	ATP	TANK AMM	ON HAND	1.0		1.0	
COEF	ALL	DS ORD	CAP	0.05		0.	
COEF	ALL	CORP TMT	CAP	2.		0.	
COEF	ASP-ATP	TANK AMM	RQUISITN	1.0		1.0	
PIPE	ATP-BDE	TANK AMM	RESUPPLY	0.63	15.9	0.	15.9
FROM	ATP	TANK AMM	ON HAND	1.0		1.0	
TO	BRIGADE	TANK AMM	ON HAND	1.0		1.0	
COEF	ATP-BDE	TANK AMM	RQUISITN	1.0		1.0	

We have left the Red priorities and durations for these activities as question marks. We are inclined to make them the same as the Blue priorities and durations, but another user might prefer other values.

The Blue priorities call for the rates of these activities to be calculated in order by origin node, starting with the node farthest from BRIGADE. The rates of activities with the same origin node will be calculated in order of destination node, starting with the node

closest to BRIGADE. This priority order will tend to fill requisitions as far forward as possible with ammunition stocks from as far back as possible. Other priority orders, with or without some tied priorities, may serve as well or better to represent Army doctrine.

6. POL DISTRIBUTION AND CONSUMPTION

Petroleum, Oil, and Lubricants (POL) is a class of supply that is not represented in the test case distributed with LDM. In this section, we discuss all of the steps necessary to add a new supply resource to LDM, using POL as the example. Before the reader begins this section, we recommend that he review Chapter 5 of the LDM Users' Manual [3], which describes the different types of records in a SUPPORT file and explains their formats and data elements.

To add a new supply resource to LDM, one must first specify activities in the SUPPORT files for how it will be distributed. Distribution of POL can be modeled in much the same way as ammunition distribution. One defines a network and introduces capacities for handling the POL at each node and transporting it along each link.

One must also specify how much of the POL will be consumed by each item of equipment and by the CSS units that provide not only capacities used in POL distribution but also capacities used in all other logistics functions. Finally, one must specify how a shortage of this resource will affect the number of weapons to engage in combat and the capacities of the CSS units to perform their tasks.

BULK POL DISTRIBUTION

Figure 6.1 shows the bulk POL distribution network for NATO, as described in [11]. The network consists of a set of fuel-processing nodes and fuel transportation links. The transport modes considered are pipeline and tanker truck; separate links have been provided for each. POL can also be transported by hoseline, rail, barge, and air, but Fig. 6.1 does not show these possibilities. The fractions in the figure dictate how much of the demand for POL at a node will be requisitioned from each of the other nodes. The nodes in the network represent locations where significant amounts of bulk POL are stored and/or issued. In principle, POL can be issued from any node, but the system is designed to issue POL almost exclusively from the DS nodes. Unlike ammunition, there are significant demands at all echelons for POL.

In the example formulation of the POL distribution function, each activity corresponds to transporting one type of POL along one of the links in Fig. 6.1. The Army uses three main types of POL: MOGAS (ordinary gasoline); diesel fuel; and JP-4 (aviation fuel). If the user considers each type separately, three activities will correspond to each link. In our example, we will model only a single, generic type of POL; for that reason, we will include only one activity for each link. Table 6.1 lists the names of the 17 activities in the example

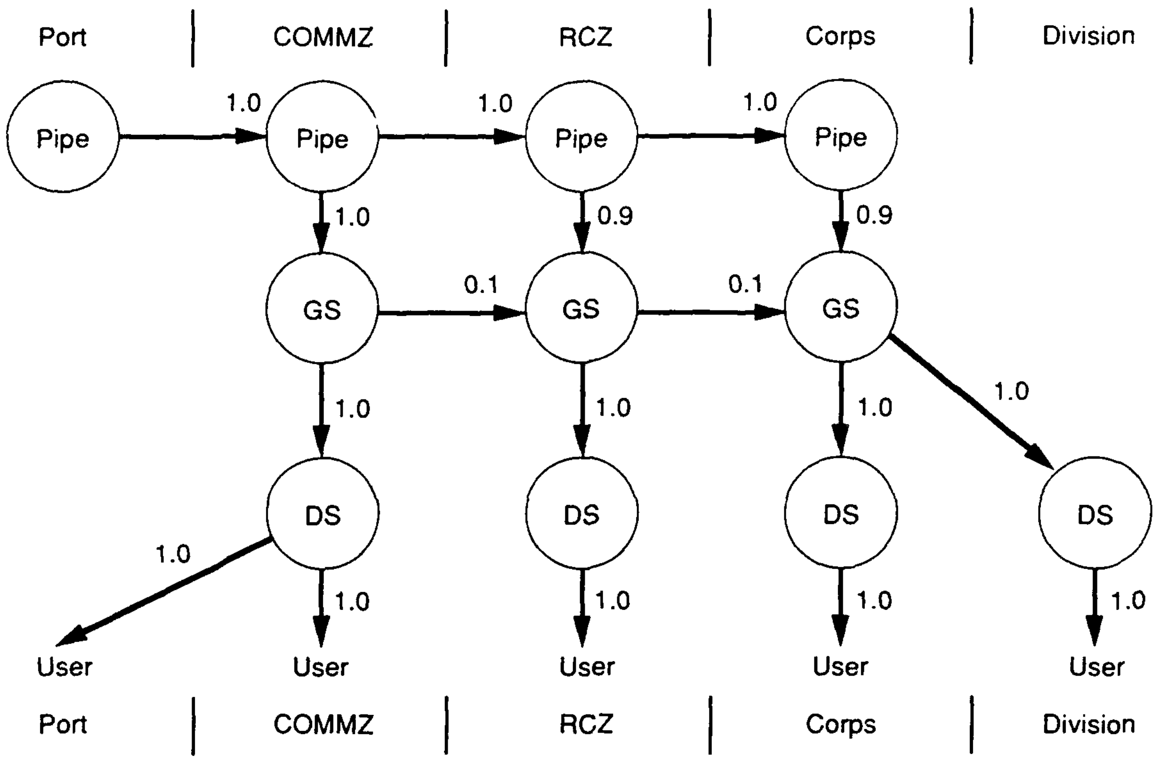

Fig. 6.1—The Bulk POL Distribution Network for NATO

formulation, as they would appear in the SUPPORT files. Because we are limited to eight characters in naming a link, the names are necessarily cryptic. However, we have attempted to make them systematic. The name of each link consists of shortened versions of its origin and destination nodes, separated by a hyphen. For example, CZG stands for the COMMZ GS node, RZD for the RCZ DS node, and so on. Table 6.2 shows the correspondence between the names of the nodes in Fig. 6.1 and the shortened names used in Table 6.1.

The same three constraints play a direct role in POL distribution as in ammunition distribution; namely, *balance* constraints, *capacity* constraints, and *requisition* constraints. In the following sections, we address each of these constraints in turn.

Balance Constraints and Duration of Activities

The balance constraints prevent more POL from being issued by a node than there is POL available. They also cause each activity to delay its deliveries of POL to its destination node by a user-specified duration for the activity, in this instance a transportation time. To implement the balance constraints, the user need only specify the activity duration on a PIPE record, and identify the node *from* which the activity takes POL in a FROM record, and

Table 6.1

Activities for Distributing POL

PORT-CZP	POL	RESUPPLY
CZP-CZG	POL	RESUPPLY
CZP-RZP	POL	RESUPPLY
CZG-CZD	POL	RESUPPLY
CZG-RZG	POL	RESUPPLY
CZD-PU	POL	RESUPPLY
CZD-CZU	POL	RESUPPLY
RZP-RZG	POL	RESUPPLY
RZP-CRP	POL	RESUPPLY
RZG-RZD	POL	RESUPPLY
RZG-CRG	POL	RESUPPLY
RZD-RZU	POL	RESUPPLY
CRP-CRG	POL	RESUPPLY
CRG-CRD	POL	RESUPPLY
CRG-DVD	POL	RESUPPLY
CRD-CRU	POL	RESUPPLY
DVD-DVU	POL	RESUPPLY

Table 6.2

Correspondence Between Short and Long Node Names

Short Name	Long Name	Short Name	Long Name	Short Name	Long Name
PORT	PORT	RZP	RCZ PIP	CRP	CORPS PIP
PU	PORT User	RZG	RCZ GS	CRG	CORPS GS
CZP	COMMZ PIP	RZD	RCZ DS	CRD	CORPS DS
CZG	COMMZ GS	RZU	RCZ User	CRU	CORPS User
CZD	COMMZ DS			DVD	DIVISION DS
CZU	COMMZ User			DVU	DIVISION User

the node *to* which the activity delivers POL in a TO record. (All three kinds of records appear in a SUPPORT file; see [3], Chapter 5.)

Two modes of transportation are represented in Fig. 6.1. We use different methods to estimate durations for activities that use different modes of transportation. We set the duration of a pipeline activity to zero. We argue that one needn't wait for POL to be delivered by pipeline because the pipeline is always full of POL.[1] Of course, there is a limit to the rate at which POL can be withdrawn from the pipeline, but this is represented by the pipeline capacity constraint, not by the duration of the pipeline activities.

[1]In NATO, the pipeline is used to transport all kinds of POL. Several kilometers of pipeline will be filled with diesel fuel, followed by several kilometers of JP-4 or MOGAS. Thus, one may have to wait several hours until the right kind of POL flows by.

To calculate the duration for activities that transport POL by tanker truck, we must know the lengths of the different links in Fig. 6.1, the transport velocities along those links, and the delay times for filling and emptying tankers. Table 6.3 shows illustrative link lengths [11].

According to Field Manual FM 55-15 [8], trucks performing line haul duties to the rear of the Corps move at an average speed of 32 km/hr; trucks performing local distribution duties to the rear of the Corps and all trucks in the Corps area and forward travel at 16 km/hr.

In [12], the following method is advanced for calculating the time required to fill or empty a tanker truck. The tanker capacity is either 5,000 or 7,500 gallons. The pumps available to fill or empty the tanker have a maximum pumping rate of 350 gpm and are assumed to operate at 75 percent of capacity. This yields an actual pumping time of $5{,}000/(350 \times 0.75)$, or 19.05 minutes to fill or empty a 5,000-gallon tanker, and 28.57 minutes for the larger 7,500-gallon tanker. To this we add 20 minutes for hooking and unhooking the pump to the tanker, as well as other delays. The total is 40 or 50 minutes, depending on the tanker size. For simplicity, we will assume that filling or emptying a tanker takes 45 minutes, or 0.75 hr, regardless of tanker size.

Durations of all the POL distribution activities appear in Table 6.4.

Capacity Constraints

Identification of Capacity Constraints. Tables 6.5 and 6.6 show the units that perform the tasks associated with the respective nodes and links of the network in Fig. 6.1, as gleaned from [10, 11, 12]. POL is received at ports and pumped into the Central European Pipeline System (CEPS). POL can be taken from the pipeline at a variety of takeoff points (nodes labeled PIPE in Fig. 6.1) for further distribution. In NATO, the pipeline and takeoff points are operated almost entirely by host nation support (HNS), so we do not identify U.S. Army units to perform these tasks.

Calculation of Capacities. The combined capacity of all CSS units available to perform a given task appears in LDM as the right-hand side of a capacity constraint. This capacity may change over time, as more CSS units are deployed into the theater. A way to calculate the capacities of CSS units is described in [2] and was briefly outlined in Section 5.

In NATO, if the CEPS were entirely devoted to supplying the U.S. Army, its capacity would be so large that it would never constrain POL supplies. However, the CEPS pipeline must also supply the Air Force, other nations, and civilians. In modeling the pipeline

Table 6.3

Illustrative Link Lengths (kilometers)

	To Node														
	PORT	COMMZ				RCZ				CORPS				DIVSN	
From Node	USR	PIP	GS	DS	USR	PIP	GS	DS	USR	PIP	GS	DS	USR	DS	USR
PORT		100													
COMMZ PIP			15			125									
COMMZ GS				50			125								
COMMZ DS	20				20										
RCZ PIP							15			125					
RCZ GS								50			125				
RCZ DS									20						
CORPS PIP											15				
CORPS GS												50		110	
CORPS DS													20		20

Table 6.4

Durations of POL Distribution Activities (all times in hours)

Activity	At 32 km/hr Dist	At 32 km/hr Time	At 16 km/hr Dist	At 16 km/hr Time	Fill + Empty	Total Duration
PORT-CZP						0.
CZP-CZG	15	0.47			1.5	1.97
CZP-RZP						0.
CZG-CZD	50	1.56			1.5	3.06
CZG-RZG	125	3.91			1.5	5.41
CZD-PU			20	1.25	1.5	2.75
CZD-CZU			20	1.25	1.5	2.75
RZP-RZG	15	0.47			1.5	1.97
RZP-CRP						0.
RZG-RZD	50	1.56			1.5	3.06
RZG-CRG	125	3.91			1.5	5.41
RZD-RZU			20	1.25	1.5	2.75
CRP-CRG			15	0.94	1.5	2.44
CRG-CRD			50	3.13	1.5	4.63
CRG-DVD			110	6.88	1.5	8.38
CRD-CRU			20	1.25	1.5	2.75
DVD-DVU			20	1.25	1.5	2.75

Table 6.5

POL Handling Tasks and Units

Node	Unit Nomenclature	SRC
PORT	Host nation support	—
PIP nodes	Host nation support	—
DS nodes	Petroleum Platoon of QM Supply Co.	29147H500 29147H520 42447L000
GS nodes	Petroleum Supply Co.	10227H500 10427L000

system, one must decide how much of its capacity should be allocated to these users—and, hence, what capacity remains for the U.S. Army.

The demand these other POL users impose on the CEPS pipeline is an *external* demand, because it is generated by users outside the LDM model. There are at least three ways to account for this external demand. One way is to ignore it. This amounts to

Table 6.6

POL Transport Tasks and Units

Link	Unit Nomenclature	SRC
Pipeline	Host nation support	—
All PIP-GS, GS-GS, and GS-DS	TMT Petroleum Co.	55018H620 55018H650 55727L200

assuming that the demand can be deferred without affecting combat performance. Because the external demand is a large fraction of the total, this approach will effectively eliminate the constraining effect of any limitation on pipeline capacity.

Another way is to set aside enough pipeline capacity to satisfy the external demand and let only the remaining capacity appear in LDM. Of course, this requires an estimate of the size of the external demand. In addition, it treats the external demand as the most important of all POL uses. Because the external demand is a large fraction of the total, this approach may impose an unrealistically severe constraint on POL supplied to the U.S. Army.

Finally, one can factor the external demand on top of the demands generated within LDM. That is, for every 100 gallons of POL consumed by users inside LDM, one might add another 400 gallons consumed by users not represented in LDM. (We don't know whether 400 is the correct number. The appropriate number can be derived from estimates of both the average external and internal demands per day.) This approach shares the available capacity proportionately between external and internal demands.

Calculation of Workloads. In the example formulation of the POL distribution function, we will define a capacity constraint for each type of unit shown in Tables 6.5 and 6.6, and one more for each pipeline segment. We express each activity rate in thousands of gallons of POL moved per 12-hour period (this is written as Kgal/12Hr).

The capacity of a *Petroleum Platoon* is normally expressed in Gals/day of POL issued; however, for convenience, we will use units of Kgal/day.[2] Thus, for each Kgal/12Hr of POL issued from a DS node, Petroleum Platoons will face a workload of 1 Kgal/12Hr, or (converting units) 2 Kgal/day. The activities that issue POL from DS nodes are those corresponding to the various DS-USER links in Fig. 6.1.

---

[2]While the Petroleum Platoon must have received and temporarily stored POL to issue it, the statement of its capacity does not explicitly recognize the work involved in these other steps. This extra work can be recognized implicitly by factoring it into the direct issuing workload as a kind of overhead. The main disadvantage of this approach is that it treats the work of receiving POL as though it occurs at the same time as the work of issuing POL.

Petroleum Supply Company capacity is also expressed in Gals/day of POL issued, with no mention of receipt of POL. Petroleum Supply Companies operate GS nodes, so the activities that generate workload for this type of unit are those corresponding to the various GS-GS and GS-DS links in Fig. 6.1. Each of these activities will generate 2 Kgal/day workload for Petroleum Supply Companies for each Kgal/12Hr of POL moved.

Workloads for *TMT Petroleum Companies* are expressed as Gal-kilometers per day; however, for convenience, we will use units of Kgal-km/day. These workloads are generated by the activities for all the links except pipelines. Each Kgal/12Hr of POL transported equals 2 Kgals/day; this can be multiplied by the link lengths (see Table 6.3) to determine the workloads in gal-km/day.

The capacity constraints for pipeline segments prevent the actual flow in the pipeline segment from exceeding a maximum permissible flow. By analogy with the other capacity constraints, the actual flow is the workload, while the maximum flow is the capacity. Each unit of workload consumes one unit of capacity.

Table 6.7 shows all the coefficients for generating CSS unit workloads for the POL distribution function, and for constraining POL flows in all the pipeline segments.

Table 6.7

Workloads Generated by POL Distribution Activities

		Petrl	TMT	Pipeline Capacities		
Activity (Kgal/12Hr)	Petrl Plt Kgal/d	Sup Co Kgal/d	Petrl Co Kgal-km/d	PORT-CZP	PCZP-RZP	RZP-CRP
PORT-CZP	—	—	—	1	—	—
CZP-CZG	—	—	30	—	—	—
CZP-RZP	—	—	—	—	1	—
CZG-CZD	—	2	100	—	—	—
CZG-RZG	—	2	250	—	—	—
CZD-PU	2	—	—	—	—	—
CZD-CZU	2	—	—	—	—	—
RZP-RZG	—	—	30	—	—	—
RZP-CRP	—	—	—	—	—	1
RZG-RZD	—	2	100	—	—	—
RZG-CRG	—	2	250	—	—	—
RZD-RZU	2	—	—	—	—	—
CRP-CRG	—	—	30	—	—	—
CRG-CRD	—	2	100	—	—	—
CRG-DVD	—	2	220	—	—	—
CRD-CRU	2	—	—	—	—	—
DVD-DVU	2	—	—	—	—	—

Requisition Constraints

To ensure that POL flows are distributed according to the distribution fractions specified in Fig. 6.1, one must introduce a requisition constraint for each link. These constraints serve the same purpose, and are formulated in the same way, as the requisition constraints for the ammunition distribution function (see Section 5). The user specifies how much POL each node is authorized. In each time period, that node has a local need for enough POL to fill its stocks on hand to the authorized quantity, less the amount already due in. The node needs enough additional POL to satisfy requisitions from nodes further forward in the POL distribution network. The local and additional needs at each node, as well as the desired flow on each link, can be calculated using Equations (5.1) to (5.4). Equations (5.3) and (5.4) require distribution fractions. These are shown in Fig. 6.1, and they also appear in Table 6.8.

Implementing the POL Distribution Function in LDM

The POL distribution function should be implemented in LDM in essentially the same way as the ammunition distribution function in Section 5. In the preceding tables, we presented all the data necessary to implement POL distribution in its simpler form, without making adjustments for errors of aggregation. We leave to the reader the task of writing the actual records for the SUPPORT files.

POL AND WEAPONS

POL and weapons are related by two mechanisms. First, the amount of POL available at the BRIGADE echelon can affect the numbers of the different kinds of weapons that can engage. Second, weapon systems consume POL, both when they are in combat and when they are not.

The Effect of POL Availability on Engaged Weapons

We specify the effect of POL shortages on the numbers of engaged weapons by requiring that a certain amount of POL be available for each weapon that engages. This is the same approach we used to specify the effects of ammunition shortages, crew shortages, and so on. We measure POL in units of thousands of gallons. Then, if λ_1 thousands of gallons of fuel must be available for each tank that engages, we add a WEAPON constraint resource for POL and introduce a new coefficient in the activity that represents the number of tanks ready to engage; namely, the BRIGADE .. TANK .. READY activity.

Table 6.8

Distribution Fractions

	To Node														
	PORT	COMMZ				RCZ				CORPS				DIVSN	
From Node	USR	PIP	GS	DS	USR	PIP	GS	DS	USR	PIP	GS	DS	USR	DS	USR
PORT		1.0													
COMMZ PIP			1.0			1.0									
COMMZ GS				1.0			0.1								
COMMZ DS	1.0				1.0										
RCZ PIP							0.9			1.0					
RCZ GS								1.0			0.1				
RCZ DS									1.0						
CORPS PIP											0.9				
CORPS GS												1.0		1.0	
CORPS DS													1.0		1.0

CONSTR	BRIGADE	POL	WEAPON				
RHS	DVU	POL	ON HAND	1.0		1.0	
PIPE	BRIGADE	TANK	READY	0.	–10.	0.	–10.
FROM	BRIGADE	TANK	WEAPON	1.		1.	
COEF	BRIGADE	TANK AMM	WEAPON	52.6		29.2	
COEF	BRIGADE	OTHR AMM	WEAPON	12.0		5.45	
COEF	BRIGADE	WPN CREW	WEAPON	4.0		4.0	
COEF	BRIGADE	POL	WEAPON	λ_1		0.	

Similar entries must be added in the BRIGADE .. POL .. WEAPON constraint for all the weapon systems that require POL. For this example, we added a POL distribution function to the Blue side only. We set all the parameters to zero for the Red side.

Values for these coefficients should probably be based on planning factors for POL consumption by the various weapons during a 12-hour engagement [13]. The value would not necessarily equal the expected consumption. Instead, it might equal a multiple (say, ten) of the expected consumption. This would allow the Brigade to maintain a POL reserve and to cut back on combat activity when the reserve dwindled. The physical fuel capacities of the different weapons may also play a role in determining values for these coefficients.

Base POL Consumption by Equipment Items

Tanks and other equipment items that do not engage in combat will consume POL at some base rate. To represent this, we introduce new entries in the resource matrix that specify the POL consumption per period for all equipment items at a given echelon. The coefficients λ_2, λ_3, and so on are the consumption rates for the various kinds of equipment. The example below is for the BRIGADE echelon; the same approach works at the other echelons as well.

STOCK	DVU	POL	ON HAND		
RHS	BRIGADE	TANK	ON HAND	$-\lambda_2$	0.
RHS	DISCOM	TANK	RESUPPLY	$-\lambda_2$	0.
RHS	BRIGADE	APC	ON HAND	$-\lambda_3$	0.
RHS	DISCOM	APC	RESUPPLY	$-\lambda_3$	0.
.					
.					
.					

Note the RHS records specifying that weapons in transit also consume POL. These are the DISCOM .. (weapon) .. RESUPPLY records. At other echelons, there will be not only weapons in transit forward to consider but also weapons in transit to the rear, and weapons

awaiting and undergoing repair. The user may specify different POL consumption rates for weapons in these different categories.

It is essential to realize that placing these coefficients in the resource matrix causes POL to be consumed by each equipment item, regardless of whether there is any POL available to be consumed. If there is no POL, or there is less than required by the weapons at an echelon, the amount of POL on hand at that echelon will be reduced to a negative number. This is a clear signal that the model has been stressed beyond its limits of validity. This situation may be corrected by making more POL available at that echelon (e.g., by adding more POL to the theater, or by improving POL distribution). Or it may be corrected by reformulating the model so that POL consumption by weapons can be reduced below the amounts specified by these coefficients. We have no suggestions for such a reformulation.

Incremental POL Consumption by Engaged Weapons

We specify the consumption of POL by weapon systems engaged in combat with a CBT_LOSS function (see [3], Chapter 4). Every weapon will use POL (except, perhaps, infantry), so every weapon will have a POL coefficient to multiply the number of that weapon that is engaged. There may also be coefficients for the number of hits that weapons of any type suffer. The records that specify the CBT_LOSS function appear in the ATTRITION file, as follows:

DEP	BRIGADE	POL	NET LOSS				
	BRIGADE	TANK	READY	η_1	ν_1	0.	0.
	BRIGADE	APC	READY	η_2	ν_2	0.	0.
	.						
	.						
	.						

The coefficients η_1 and η_2 are the Blue coefficients of engaged weapons, while ν_1 and ν_2 are the Blue coefficients of weapons hit. The corresponding coefficients for Red are set to zero.

Every weapon consumes POL at the base rate, even those that are engaged. Thus the coefficients in the CBT_LOSS records should specify the *incremental* amount of POL consumed by an engaged or hit weapon, not the *total* amount. Specifying the total amount would mean double counting the base consumption specified by the resource matrix entries.

POL AND CSS UNITS

Like weapons, CSS units are related to POL by two mechanisms. First, the capacity of a CSS unit to perform its function must be affected by the amount of POL available. Otherwise, LDM will not show any effect of POL shortages on the performance of the

logistics support structure. Second, each CSS unit consumes POL, and it consumes different amounts of POL depending on how much of its capacity is in use. We represent these mechanisms in substantially the same way for CSS units as we did for weapons.

The Effect of POL Availability on CSS Unit Capacity

In Section 5, we calculated the available capacity of GS ORD companies with the following records:

CONSTR	ALL	GS ORD	CAP		
RHS	ALL	GS ORD	UNIT	1.0	0.0

We no longer wish to calculate the capacity in this way, so we need to delete these records from the formulation of the ammunition distribution function, along with the corresponding records for the other CSS units.

Now we will require that a specified amount of POL be available per GS ORD company, before we count that company's capacity as being available for ammunition handling. To do this, we first define new constraints, analogous to the BRIGADE .. (resource) .. WEAPON constraints for weapons. There will be one such constraint for each resource that appears in the mix of resources that make up a unit of GS ORD capacity. These are GS ORD companies themselves, and POL. The required SUPPORT records are as follows:

CONSTR	EAC	POL	AVAIL		
RHS	CZU	POL	ON HAND	1.0	0.0
RHS	RZU	POL	ON HAND	1.0	0.0
CONSTR	ALL	GS ORD	AVAIL		
RHS	ALL	GS ORD	UNIT	1.0	0.0

The first of these constraints has a right-hand side equal to all the POL available to units at echelons above Corps (EAC). This consists of POL at the COMMZ User and RCZ User nodes of Fig. 6.1. The right-hand side of the second constraint equals the total capacity that GS ORD companies in the theater would have if ample POL were available.

We will still need a constraint on the available GS ORD capacity, and we will still call it ALL .. GS ORD .. CAP, but now we will initialize its right-hand side to zero. Then we will define an activity, analogous to the BRIGADE .. (weapon) .. READY activities for weapon systems, that will calculate the amount of GS ORD capacity that is ready for use.

CONSTR	ALL	GS ORD	CAP				
PIPE	ALL	GS ORD	READY	0.	?	0.	0.

COEF	EAC	POL	AVAIL	λ_4	0.
COEF	ALL	GS ORD	AVAIL	1.	1.
COEF	ALL	GS ORD	CAP	–1.	–1.

We have left the priority of this activity as a question mark, but a number must be filled in for LDM to work. This priority, and the priorities of activities that define available capacities for other types of CSS units, should precede the activities that make use of GS ORD capacity (in this example, the ammunition resupply activities). All these activities should probably have the same priority, so that they share the available POL.

The coefficient λ_4 measures the amount of POL that must be on hand, in thousands of gallons, to make one unit of GS ORD capacity available. The value for this coefficient, and corresponding ones for other types of CSS units, should probably be based on the likely POL consumption by that unit type during a 12-hour period. As with the corresponding coefficients of weapons (coefficient λ_1), the value would not necessarily equal the expected consumption. Instead, it might equal a multiple (say, ten) of the expected consumption. This would allow the logistics support system to maintain a POL reserve and to cut back on activity rates when the reserve dwindled.

Base POL Consumption by Unemployed CSS Units

CSS units whose capacity is not employed may nevertheless consume POL, albeit at a lower rate than units whose capacity is employed. To represent this, we introduce new entries in the resource matrix that specify the POL consumption per period for all equipment items at a given echelon. The coefficients λ_5, λ_6, and so on are the rates at which the various kinds of CSS units consume POL from the indicated source.

STOCK	CZU	POL	ON HAND		
RHS	ALL	GS ORD	UNIT	$-\lambda_5$	0.
RHS	ALL	THEA TMT	UNIT	$-\lambda_6$	0.

In the preceding example, the indicated source is the COMMZ User node of Fig. 6.1. The same units can also consume POL from other sources. For example:

STOCK	RZU	POL	ON HAND		
RHS	ALL	GS ORD	UNIT	$-\lambda_7$	0.
RHS	ALL	THEA TMT	UNIT	$-\lambda_8$	0.

The sum over all sources of the coefficients for a given type of unit is the base POL consumption rate for that unit, when the unit is not employed.

Placing these coefficients in the resource matrix causes POL to be consumed by each CSS unit, regardless of whether there is any POL available to be consumed. If there is no POL, or there is less than required by the CSS units at an echelon, the amount of POL on hand at that echelon will be reduced to a negative number. This is a clear signal that the model has been stressed beyond its limits of validity. This problem can be avoided if one assumes that the base POL consumption is zero. Lack of data may force the user to make an arbitrary assumption about base POL consumption; the assumption that the base rate is zero may be as reasonable as any other.

Incremental POL Consumption by Employed CSS Units

The incremental consumption of POL by a CSS unit actively performing its function can be represented in the activities that use that unit's capacity. In the ammunition distribution example, one of the activities transported ammunition from PORT to TSA. (Exactly which SUPPORT records appear in the definition of this activity depends on whether one uses the formulation of the ammunition distribution function with or without adjustments for aggregation errors.) We would add a coefficient to represent POL consumption as follows:

PIPE	PORT-TSA	TANK AMM	RESUPPLY	11.13	15.2	0.	0.
	.						
	.						
COEF	CZU	POL	ON HAND	λ_9		0.	

For this activity, we take the POL from the COMMZ User node of Fig. 6.1. Similar coefficients must be introduced in the other ammunition resupply activities. For other activities, we might take some from the COMMZ User and some from the RCZ User, and even some from the CORPS User. The LDM user must decide how to apportion the POL consumption among these nodes.

The coefficient λ_9 should specify the *incremental* amount of POL consumed per hundred pounds of ammunition transported, not the *total* amount. As with weapons, we specify consumption rates for units not actively performing their functions by introducing new entries into the resource matrix. Specifying λ_9 as the total consumption of the units would mean double counting the base consumption specified by the resource matrix entries.

The coefficient λ_9 must include POL consumption by both the GS ORD company and the Theater TMT Company (the activity consumes capacity of both types of companies). These coefficients play the same role for CSS units as do the coefficients in the CBT_LOSS functions for engaged weapons.

OTHER ARMY POL DEMANDS

We have not mentioned many kinds of Army units that will deploy to the NATO theater of operations. These include supply units, military police, engineers, medical units, and many others. All of these units will consume POL.

We have considered three approaches for dealing with the POL consumed by units not represented in LDM. First, we can ignore it. This amounts to assuming that depriving these units of POL supplies will have no effect on the Army's combat performance. A simulation based on this assumption will yield the most optimistic results, for it makes the greatest supplies of POL and POL distribution capacity available to the subset of POL consumers represented in LDM.

Second, we can estimate the POL consumed per day by the unrepresented units and calculate the flows implied by these consumption rates through the nodes and links of Fig. 6.1. Then we can subtract the consumption from the available POL supplies, and the flows from the capacities of the various CSS units identified previously. This gives the unrepresented units first priority for POL supplies and distribution capacity, leaving the units represented in LDM to compete for the remainder. A simulation based on this approach will yield the most pessimistic results, for it makes the least amount of POL available to consumers represented in LDM.

The third approach is an intermediate one, between the first two. As in the second approach, we can estimate the demands for POL by the unrepresented units. Then we can inflate all the POL consumption factors for POL consumers represented in LDM so that they include a pro rata share of POL consumption by unrepresented consumers.

Although the third approach might appear more likely to yield accurate results than either of the other two approaches, it is actually less desirable than a combination of the first two approaches. We believe that the best approach is to run the simulation twice, once with no adjustment for POL consumption by unrepresented units (approach one), and once more with POL supplies and distribution capacity set aside for the use of unrepresented units before the simulation even begins (approach two). The results from the two simulations should bracket the "true" results. If there is little difference between the two simulations—either because both have severe POL supply or capacity shortfalls or because neither does—the conclusions one draws about POL supplies and distribution will be robust. We cannot say whether a simulation using the third approach is optimistic or pessimistic; conclusions drawn from such a simulation may well not be robust.

On the other hand, simulations using approaches one and two may differ substantially. This situation may arise if the POL demanded by unrepresented units is a

large fraction of the total POL demanded by all units. In this case, further study of POL supplies and/or distribution is warranted. Either some of the unrepresented units must be added to LDM, or a separate study of POL supplies and distribution must be performed to provide a reasonable basis for allocating supplies and capacity between represented and unrepresented units.

7. THE MAINTENANCE SYSTEM

OVERVIEW

Figure 7.1 shows the part of the maintenance system we will formulate for LDM. Before the reader begins this section, we recommend that he review Chapter 5 of the LDM Users' Manual [3], which describes the different types of records in a SUPPORT file and explains their formats and data elements. A capsule description of the maintenance system and how it is intended to function can be found in Field Manual FM 100-10 [14].

Briefly, equipment at any echelon can require maintenance. Combat equipment at the BRIGADE echelon can be damaged in battle or fail in ordinary use. (This is called Reliability, Availability, and Maintainability—or RAM—failure.) Other equipment at other echelons can also suffer RAM failures. If possible, repairs will be performed by the unit that owns the equipment (Unit Maintenance), an option not shown in the figure.

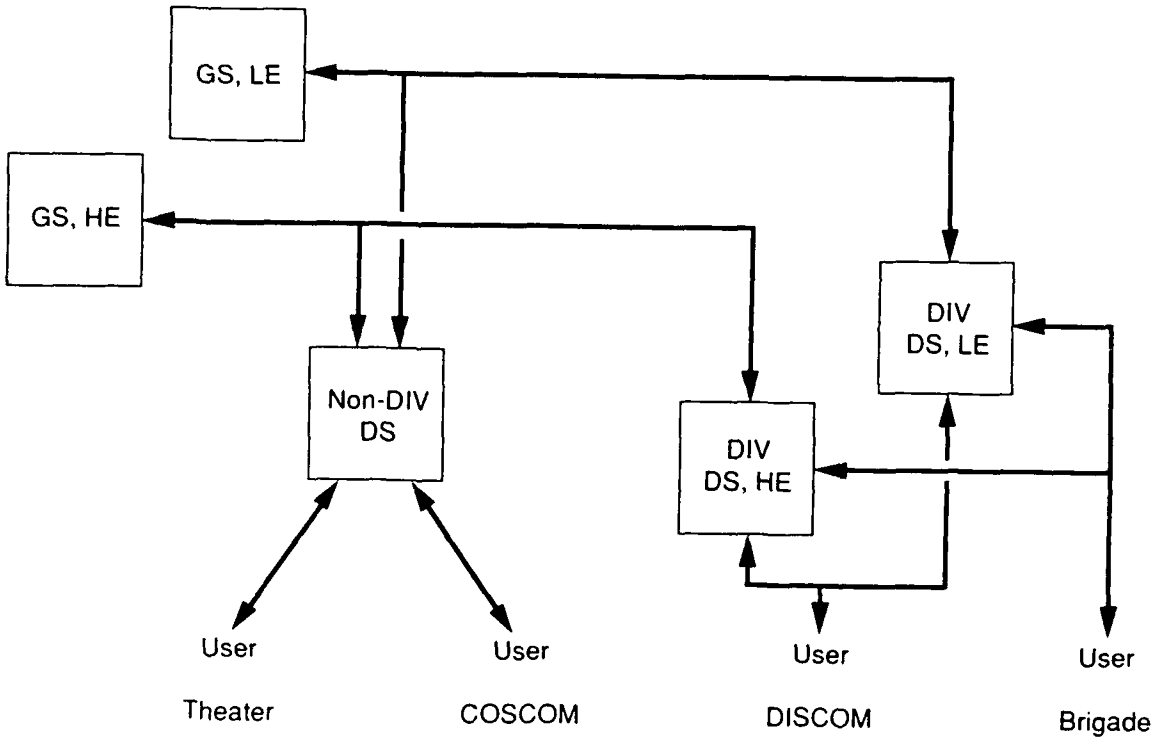

Fig. 7.1—The Maintenance System

Equipment requiring repairs too complex for unit maintenance is turned over to a DS Maintenance Company. At the Division Support Command (DISCOM), DS maintenance is divided between Light Equipment Maintenance Companies (represented by the DIV DS, LE node in the figure) and Heavy Equipment Maintenance Companies (represented by the DIV DS, HE node). Light equipment maintenance involves work on such equipment items as communications and intelligence gear, which typically requires relatively light tools. Heavy equipment maintenance involves tasks that require heavier tools, such as automotive repairs to tanks and trucks. At higher echelons (COSCOM and THEATER in the figure), both kinds of maintenance are done by a single Nondivisional DS Maintenance Company (the NON-DIV, DS node).

Modern Army equipment has been designed so that, when it fails, the defective or damaged component can be replaced by a working part. The equipment item can then be returned to operation, while the damaged component awaits a convenient time for repair. According to FM 100-10, the removal and replacement of the damaged component is to be done by DS Maintenance Companies, while the actual repair of the component is the responsibility of GS Maintenance Companies. Work on these components is divided between Light Equipment and Heavy Equipment GS Maintenance Companies (the GS, LE and GS, HE nodes in the figure).

Work that cannot be performed even by GS Maintenance Companies may be referred to depots. Typically, the depots will completely overhaul or rebuild equipment items or major subsystems of equipment items. Depots are not shown in the figure, and they are not included in the formulation of the maintenance function for LDM.

Maintenance Units

Table 7.1 identifies the kinds of maintenance units associated with the nodes in Fig. 7.1. There are many special-purpose maintenance units that a complete formulation of the maintenance function should consider, but that we do not mention here. In addition to a myriad of small maintenance teams[1] are included Aviation Intermediate Maintenance units, units to maintain medical equipment, and units to maintain watercraft. The simplest way to incorporate them into the formulation presented here is to inflate the capacities and workloads of the units in Table 7.1 to include allowances for these new unit types. Another

[1] For example, small maintenance teams include the GS Radar Repair Team, SRC 43237J503; the GS SIGINT/Electronic Warfare Repair Team, SRC 43237J504; the GS COMSEC Repair Team, SRC 43237J505; the GS Turbine Engine Repair Team, SRC 43237J508; the GS Fire Control Instrument Repair Team, SRC 43238J501; the GS Artillery Repair Team, SRC 43238J502; and the GS Fire Control Systems Repair Team, SRC 43238J503.

Table 7.1

Maintenance Tasks and Units

Node	Unit Nomenclature	SRC
DIV DS, LE	Maint. Co., Light Equip., Div.	43007J200 43007J400 43007L000
DIV DS, HE	Maint. Co., Heavy Equip., Div.	43008J200 43008J400 43008L000
NON-DIV DS	Maint. Co., Non-Div., DS	29209H900 43209L000
GS, LE	Maint. Co., Light Equip., GS	29134H200 43237J500 43637L100
GS, LE	2nd Shift, Light Equip., GS	43237J520 43637L200
GS, HE	Maint. Co., Heavy Equip., GS	29137H200 43238J500 43638L100
GS, HE	2nd Shift, Heavy Equip., GS	43238J520 43638L200

way is to add nodes and links to Fig. 7.1. This would require that one define additional kinds of maintenance capacities and workloads, thus expanding and complicating the formulation of the maintenance function. However, such an expansion could be necessary if the LDM user wanted to single out for analysis a particular kind of maintenance (e.g., aviation).

Capacities of maintenance companies are typically expressed in terms of maintenance man-hours available per year, which we will convert to hours available per 12-hour time period. Often, man-hours of one or a few particular Military Occupational Specialties (MOSs) are selected to represent the capacity of the unit.[2] We need only one capacity for each Divisional DS company, but for the Nondivisional DS Company we must define separate capacities for light and heavy maintenance. We will assume that Nondivisional DS

[2]TOE descriptions can be found in [10]. An examination of the TOEs for the units in Table 7.1 suggests that the MOSs that best characterize light equipment maintenance are 29E, Communications-Electronics Radio Repairer; 52C, Utilities Equipment Repairer; 52D, Power Generation Equipment Repairer; and 63J, Quartermaster and Chemical Equipment Repairer. Similarly, the MOSs that best characterize heavy equipment maintenance are 45K, Tank Turret Repairer; 62B, Construction Equipment Repairer; 63H, Track Vehicle Repairer; and 63W, Wheel Vehicle Repairer. For further discussion, see [2].

Companies are sufficiently mobile that their capacity can be used wherever needed in the THEATER or COSCOM echelons, and therefore the echelons will not have separate capacity constraints. The following SUPPORT records will calculate the capacities of the maintenance units.

CONSTR	ALL	DV_DS_LE	CAP		
RHS	ALL	DV_DS_LE	UNIT	1.	1.
CONSTR	ALL	DV_DS_HE	CAP		
RHS	ALL	DV_DS_HE	UNIT	1.	1.
CONSTR	ALL	ND_DS_LE	CAP		
RHS	ALL	ND_DS_LE	UNIT	1.	1.
CONSTR	ALL	ND_DS_HE	CAP		
RHS	ALL	ND_DS_HE	UNIT	1.	1.
CONSTR	ALL	GS_LE	CAP		
RHS	ALL	GS_LE	UNIT	1.	1.
CONSTR	ALL	GS_HE	CAP		
RHS	ALL	GS_HE	UNIT	1.	1.

The right-hand sides of the UNIT constraints will contain the capacities of the different unit types available in the theater. They may be increased from time to time by records in the TIME_PHASE file that represent the deployment of additional maintenance units to the theater.

Maintenance-Related Transportation Requirements

We have not identified units with the links in Fig. 7.1. This is because maintenance-related transportation requirements cannot be calculated so simply from demands levied by using units as can transportation requirements for POL or ammunition. Typically, the using unit provides a broken equipment item to a maintenance company near the user. The broken equipment item is transported only a short distance. Sometimes, a team from the maintenance company is sent to the equipment item. The maintenance unit (or team) will often merely remove and replace a damaged or defective component, and the equipment item will be returned to the using unit. The component may then be transported a considerable distance to be repaired. Sometimes, the equipment item is beyond repair and must be replaced by an equipment item transported from a port or the THEATER echelon.

Thus, there are transportation requirements for maintenance teams, for spare parts, and for equipment items. Transportation of maintenance teams is the responsibility of the maintenance units themselves, and they are supposedly equipped to perform this task. Studies at RAND suggest that the transportation requirements for spares and repair parts

will be small, especially in comparison with ammunition distribution requirements.[3] The bulk of equipment item transportation probably occurs in the transport of replacement equipment from the THEATER echelon to using units. The demand for this piece of maintenance-related transportation can be calculated from permanent equipment losses; the manner of calculation is essentially identical to the calculation of transportation requirements for ammunition or POL.

Data Sources

A number of parameters are needed to formulate the maintenance function, as suggested in this section. These are:

- Failure factors, denoted by ff_i.
- Repair times, denoted by rt_i.
- Maintenance man-hours consumed per repair, denoted by mmh_i.
- Transportation times, denoted by tt_i.

As with the POL example from Section 6, we will add the maintenance function only to the Blue side. These parameters will be set to zero for the Red side.

These parameters are needed at a high level of aggregation. Failure factors will be used to estimate the total amount of work generated for Light and Heavy Equipment DS maintenance, rather than the amount of work for each MOS or the number of each failed component. Repair times and maintenance man-hours per repair will be averages over all the individual maintenance tasks performed by Light or Heavy Equipment maintenance units.

Failure factors (for RAM failures), repair times, and maintenance man-hours per repair for each equipment item should be tracked by the Program Managers (PMs) for the various subsystems of that item. The PMs will be found at the Major Subordinate Commands of the Army Materiel Command (AMC). Among the sources of information they may suggest for these parameters are the following.

The Army's Sample Data Collection (SDC) system [16] collects data on RAM failure rates and repair times. These data are collected for individual components of an item of

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[3]For example, see [15]. This Note estimates that a Corps' (three heavy divisions) worth of M1 tanks will require only 3,000 pounds of lift per day to provide all the required high-technology (mostly electronics) spare parts. We will multiply by ten to account for all spare parts, rather than just the high-technology ones, and by ten again to account for the remaining weapon systems—surely a generous allowance. Then the Corps will need 150 tons per day of lift to supply all spare parts requirements. By contrast, estimates of the ammunition consumption of a heavy division range from 2,000 to almost 4,000 tons per day—i.e., more than 6,000 tons/day for the Corps.

equipment and must be aggregated to average failure rates and repair times for jobs going to the Light Equipment and Heavy Equipment DS maintenance companies.

Data from Sustainability Predictions for Army Spare Components Requirements for Combat (SPARC) [17] provide failure factors for battle damage. These data are also provided at the component level of detail.

The Maintenance Allocation Chart (MAC) for an item of equipment describes where each possible maintenance task will be done on that equipment. One might be able to determine from the MAC chart whether the failure of a particular component results in a Light or Heavy Equipment maintenance task. The MAC charts also provide engineering estimates of the number of maintenance man-hours that will be spent per maintenance task; these, too, can be aggregated to provide average maintenance man-hours per Light and Heavy Equipment DS repair.

To allocate maintenance workloads between Light and Heavy Equipment maintenance, one might also refer to the Manpower Requirements Criteria (MARC) data [18]. For each equipment item, these data specify the maintenance man-hour requirement it generates in peacetime for each MOS at the unit, DS, and GS levels of maintenance. In discussing the capacities of maintenance units, we identified certain MOSs that were characteristic of Light versus Heavy Equipment maintenance. If one assumes that the average maintenance man-hours per repair are the same for Light and Heavy Equipment maintenance, the allocation of workload should be proportional to the maintenance man-hour requirements.

Another possible source for RAM failure factors, repair times, and maintenance man-hours per repair is the Standard Army Maintenance System (SAMS) [16].

Transportation times can be estimated from typical distances and velocities for the various transportation activities. Distances and velocities have already been established for use in Army studies that use the FASTALS model [19], and they can be obtained from FASTALS input files.

We have not actually performed the analyses needed to evaluate the parameters identified in this section. However, RAND has considerable experience with the problems of estimating parameters like these, and it is typically an enormous undertaking. Not all the parameters can be obtained from the same data system, and some parameters must be estimated using data from two or more systems. The data are usually incomplete and liberally sprinkled with errors. Different data systems are inconsistent. Thus, a huge amount of work remains for the reader who wants to implement the maintenance function formulated in Section 7.

MAINTENANCE AND RESUPPLY OF COMBAT EQUIPMENT

In this part of Section 7, we formulate a support structure for LDM that repairs combat equipment and returns it to using units. The structure we will implement is shown in Fig. 7.2. Each circle represents a constraint in the LDM formulation, and each link represents an activity. The large shaded boxes surrounding groups of nodes correspond to the maintenance units shown in Fig. 7.1.

Activities

We will represent the maintenance and resupply of each type of combat equipment by 28 activities. Table 7.2 lists these activities for the type of equipment named TANK; they must be replicated for each of the other types of equipment. The resource called TANK PRT (see activities 12 through 19) represents all the types of components that are used in the repair of equipment type TANK. There is a similar resource for each equipment type. The activities are listed in the order in which we wish LDM to calculate them. This is also the order in which we will describe them, except for discussing the DS REPR activities before the TANK PRT .. GS REPR and TANK PRT .. RESUPPLY activities.

The EVACUATE and RAM FAIL activities calculate the maintenance workload involved in the repair of combat equipment. The EVACUATE activity calculates battle damage repair requirements, while the RAM FAIL activities calculate the maintenance requirements for combat equipment that fails in ordinary use.

Modern Army equipment is designed with removable components. The DIAGNOSE activities represent the discovery and removal of the failed component, and the shipment of that component to the appropriate GS Maintenance unit for repair. The repair of the equipment item is completed by a DS REPR activity, which installs the appropriate component in the equipment to render it operational once more. If the DS Maintenance Company has the appropriate component in stock, it may install a working component in the equipment item without waiting for the failed component from that equipment item to be repaired and returned. However, if the needed component is not available, it must be repaired by a GS REPR activity and returned to the DS Maintenance Company by a TANK PRT .. RESUPPLY activity.

Finally, the TANK .. RESUPPLY activities calculate the quantities of equipment sent from higher echelons to replace equipment that is abandoned or destroyed, and that cannot be replaced from maintenance.

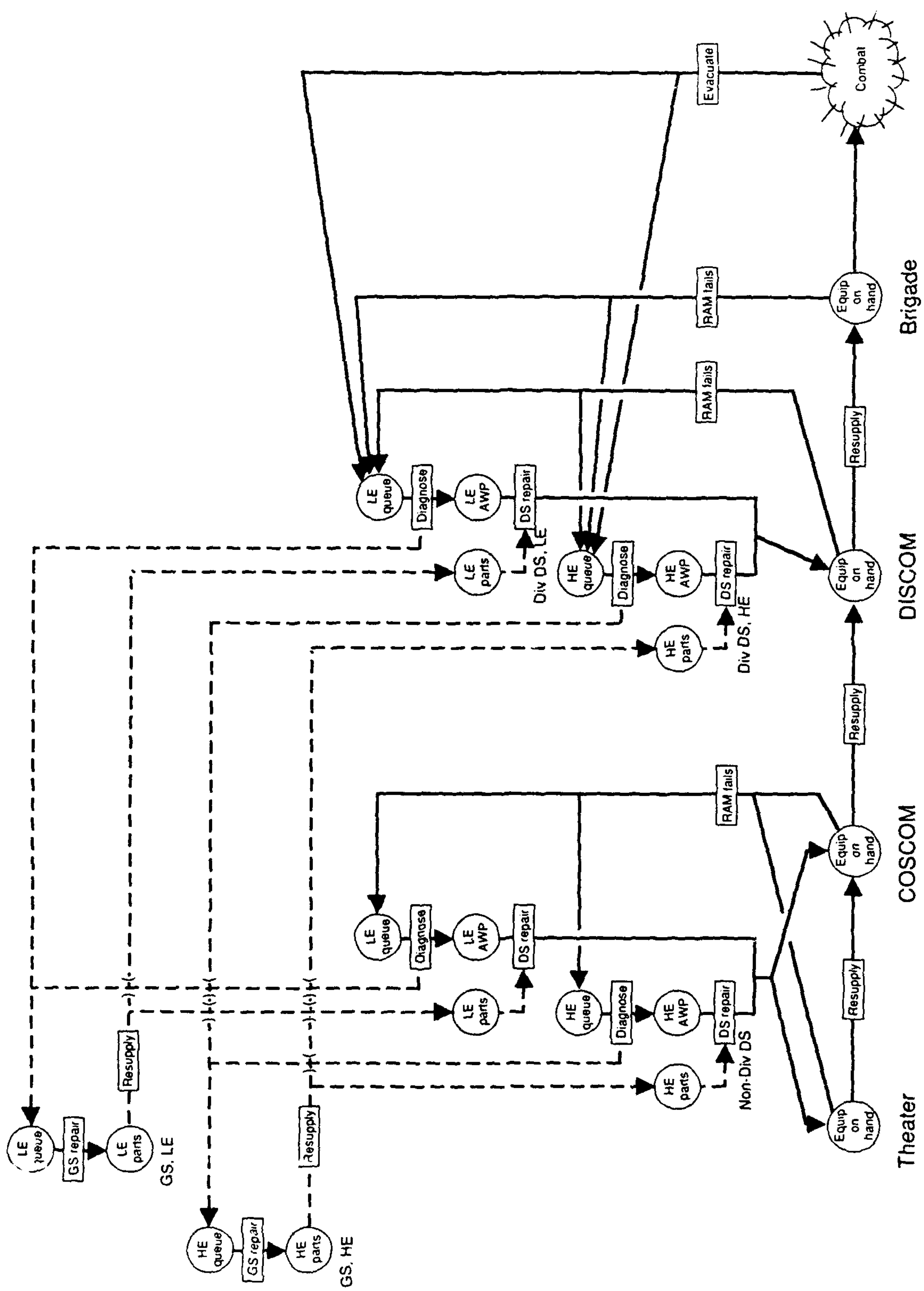

Fig. 7.2—Repair and Resupply of Combat Equipment

Table 7.2

Activities for Maintenance and Resupply of Combat Equipment

1.	BRIGADE	TANK	EVACUATE	15.	DV_DS_HE	TANK PRT	RESUPPLY
2.	BRIGADE	TANK	RAM FAIL	16.	CS_DS_LE	TANK PRT	RESUPPLY
3.	DISCOM	TANK	RAM FAIL	17.	CS_DS_HE	TANK PRT	RESUPPLY
4.	COSCOM	TANK	RAM FAIL	18.	TH_DS_LE	TANK PRT	RESUPPLY
5.	THEATER	TANK	RAM FAIL	19.	TH_DS_HE	TANK PRT	RESUPPLY
6.	DV_DS_LE	TANK	DIAGNOSE	20.	DV_DS_LE	TANK	DS REPR
7.	DV_DS_HE	TANK	DIAGNOSE	21.	DV_DS_HE	TANK	DS REPR
8.	CS_DS_LE	TANK	DIAGNOSE	22.	CS_DS_LE	TANK	DS REPR
9.	CS_DS_HE	TANK	DIAGNOSE	23.	CS_DS_HE	TANK	DS REPR
10.	TH_DS_LE	TANK	DIAGNOSE	24.	TH_DS_LE	TANK	DS REPR
11.	TH_DS_HE	TANK	DIAGNOSE	25.	TH_DS_HE	TANK	DS REPR
12.	GS_LE	TANK PRT	GS REPR	26.	COSCOM	TANK	RESUPPLY
13.	GS_HE	TANK PRT	GS REPR	27.	DISCOM	TANK	RESUPPLY
14.	DV_DS_LE	TANK PRT	RESUPPLY	28.	BRIGADE	TANK	RESUPPLY

REORDER Constraints on Equipment

Each echelon is authorized a certain quantity of each type of equipment. In the course of the simulation, equipment that is abandoned or destroyed must be replaced from either repairs or stocks of equipment at higher echelons. We define the following REORDER constraints to calculate the amount of equipment that must be added to the equipment inventories at the various echelons to make them equal to the authorizations. We define them cumulatively. The BRIGADE echelon can order only enough so that its inventories will equal its authorizations. But the DISCOM may order enough so that the sum of its inventories plus the BRIGADE inventories will equal the sum of its authorizations plus the BRIGADE authorizations. Similarly, the COSCOM may order enough equipment so that BRIGADE plus DISCOM plus COSCOM inventories equal BRIGADE plus DISCOM plus COSCOM authorizations.

CONSTR	BRIGADE	TANK	REORDER		
RHS	BRIGADE	TANK	AUTH	1.0	1.0
RHS	BRIGADE	TANK	ON HAND	–1.0	–1.0
RHS	BRIGADE	TANK	RESUPPLY	–1.0	–1.0
CONSTR	DISCOM	TANK	REORDER		
RHS	BRIGADE	TANK	AUTH	1.0	1.0
RHS	BRIGADE	TANK	ON HAND	–1.0	–1.0
RHS	BRIGADE	TANK	RESUPPLY	–1.0	–1.0
RHS	BRIGADE	TANK	RAM FAIL	–1.0	–1.0
RHS	BRIGADE	TANK	EVACUATE	–1.0	–1.0
RHS	DISCOM	TANK	AUTH	1.0	1.0
RHS	DISCOM	TANK	ON HAND	–1.0	–1.0
RHS	DISCOM	TANK	RESUPPLY	–1.0	–1.0
RHS	DISCOM	TANK	RAM FAIL	–1.0	–1.0
RHS	DV_DS_LE	TANK	QUEUE	–1.0	–1.0
RHS	DV_DS_LE	TANK	DIAGNOSE	–1.0	–1.0
RHS	DV_DS_LE	TANK	AWP	–1.0	–1.0
RHS	DV_DS_LE	TANK	DS REPR	–1.0	–1.0
RHS	DV_DS_HE	TANK	QUEUE	–1.0	–1.0
RHS	DV_DS_HE	TANK	DIAGNOSE	–1.0	–1.0
RHS	DV_DS_HE	TANK	AWP	–1.0	–1.0
RHS	DV_DS_HE	TANK	DS REPR	–1.0	–1.0
CONSTR	COSCOM	TANK	REORDER		
RHS	BRIGADE	TANK	AUTH	1.0	1.0
RHS	BRIGADE	TANK	ON HAND	–1.0	–1.0
RHS	BRIGADE	TANK	RESUPPLY	–1.0	–1.0
RHS	BRIGADE	TANK	RAM FAIL	–1.0	–1.0
RHS	BRIGADE	TANK	EVACUATE	–1.0	–1.0
RHS	DISCOM	TANK	AUTH	1.0	1.0
RHS	DISCOM	TANK	ON HAND	–1.0	–1.0
RHS	DISCOM	TANK	RESUPPLY	–1.0	–1.0

RHS	DISCOM	TANK	RAM FAIL	–1.0	–1.0
RHS	DV_DS_LE	TANK	QUEUE	–1.0	–1.0
RHS	DV_DS_LE	TANK	DIAGNOSE	–1.0	–1.0
RHS	DV_DS_LE	TANK	AWP	–1.0	–1.0
RHS	DV_DS_LE	TANK	DS REPR	–1.0	–1.0
RHS	DV_DS_HE	TANK	QUEUE	–1.0	–1.0
RHS	DV_DS_HE	TANK	DIAGNOSE	–1.0	–1.0
RHS	DV_DS_HE	TANK	AWP	–1.0	–1.0
RHS	DV_DS_HE	TANK	DS REPR	–1.0	–1.0
RHS	COSCOM	TANK	AUTH	1.0	1.0
RHS	COSCOM	TANK	ON HAND	–1.0	–1.0
RHS	COSCOM	TANK	RESUPPLY	–1.0	–1.0
RHS	COSCOM	TANK	RAM FAIL	–1.0	–1.0
RHS	CS_DS_LE	TANK	QUEUE	–1.0	–1.0
RHS	CS_DS_LE	TANK	DIAGNOSE	–1.0	–1.0
RHS	CS_DS_LE	TANK	AWP	–1.0	–1.0
RHS	CS_DS_LE	TANK	DS REPR	–1.0	–1.0
RHS	CS_DS_HE	TANK	QUEUE	–1.0	–1.0
RHS	CS_DS_HE	TANK	DIAGNOSE	–1.0	–1.0
RHS	CS_DS_HE	TANK	AWP	–1.0	–1.0
RHS	CS_DS_HE	TANK	DS REPR	–1.0	–1.0

Included in the inventories of equipment at an echelon are quantities involved in various activities. For example, the RHS .. COSCOM .. TANK .. RESUPPLY record refers to tanks that are due in to the COSCOM from the THEATER.

We do not define a REORDER constraint for the THEATER echelon. There is no higher echelon from which the THEATER can requisition replacement equipment. Therefore, there is no point in calculating how much equipment the THEATER would be allowed to requisition.

Maintenance Requirements of Combat Equipment

Battle Damage. Equipment at the BRIGADE echelon can be damaged in battle. We model this in the same way as in the test case (see the LDM Users' Manual). The LDM combat module generates hits on weapons, from which a CBT_LOSS function calculates the number of weapons available for recovery and evacuation. Activities defined in one of the SUPPORT files recover and then evacuate such battle-damaged equipment as the available recovery vehicles and heavy equipment transporters (HETs) make possible. The EVACUATE activity also generates several different maintenance workloads that are proportional to the number of equipment items that have been successfully evacuated. As an example, we list the SUPPORT records that EVACUATE the TANK equipment item.

PIPE	BRIGADE	TANK	EVACUATE	0.0	0.31	0.0	0.31
FROM	BRIGADE	TANK	NEED EVC	1.0		1.0	
TO	DV_DS_LE	TANK	QUEUE	ff_1		0.	
TO	DV_DS_HE	TANK	QUEUE	ff_2		0.	
TO	BRIGADE	TANK	CODE H	ff_3		0.	
COEF	BRIGADE	EVAC CAP	RHS	1.0		1.0	

The failure factors ff_i specify the fractions of evacuated tanks that require light equipment maintenance or heavy equipment maintenance, or that are beyond repair (Code H). In an earlier section, we discussed sources of data for evaluating these (and other) parameters.

RAM Failures. Just as equipment fails in peacetime, when there is no combat activity, equipment may fail in wartime for reasons other than combat. These RAM failures can occur at any echelon. One way to represent these phenomena in a SUPPORT file is to estimate RAM failures of equipment as a fixed proportion of the equipment on hand.

RAM failures can be represented in two steps. First, one must calculate the appropriate proportion of on-hand equipment at an echelon that will fail in each time period. In the following example, the proportion for Blue is specified as ff_4 (see the RHS record). We do not specify parameters for Red.

CONSTR	BRIGADE	TANK	R-FAILS		
RHS	BRIGADE	TANK	ON HAND	ff_4	0.
CONSTR	DISCOM	TANK	R-FAILS		
RHS	DISCOM	TANK	ON HAND	ff_4	0.
CONSTR	COSCOM	TANK	R-FAILS		
RHS	COSCOM	TANK	ON HAND	ff_4	0.
CONSTR	THEATER	TANK	R-FAILS		
RHS	THEATER	TANK	ON HAND	ff_4	0.

A RAM FAIL activity then removes the failed equipment from ON-HAND status and deposits user-specified fractions of it in the Light Equipment and Heavy Equipment Maintenance Company queues.

PIPE	BRIGADE	TANK	RAM FAIL	0.	1.01	0.	1.01
FROM	BRIGADE	TANK	ON HAND	1.		1.	
TO	DV_DS_LE	TANK	QUEUE	ff_5		0.	
TO	DV_DS_HE	TANK	QUEUE	ff_6		0.	
COEF	BRIGADE	TANK	R-FAILS	1.0		1.0	
COEF	BRIGADE	TANK	REORDER	–1.0		–1.0	
PIPE	DISCOM	TANK	RAM FAIL	0.	1.11	0.	1.11
FROM	DISCOM	TANK	ON HAND	1.		1.	
TO	DV_DS_LE	TANK	QUEUE	ff_5		0.	
TO	DV_DS_HE	TANK	QUEUE	ff_6		0.	

COEF	DISCOM	TANK	R-FAILS	1.0		1.0	
PIPE	COSCOM	TANK	RAM FAIL	0.	1.21	0.	1.21
FROM	COSCOM	TANK	ON HAND	1.		1.	
TO	CS_DS_LE	TANK	QUEUE	ff_5		0.	
TO	CS_DS_HE	TANK	QUEUE	ff_6		0.	
COEF	COSCOM	TANK	R-FAILS	1.0		1.0	
PIPE	THEATER	TANK	RAM FAIL	0.	1.31	0.	1.31
FROM	THEATER	TANK	ON HAND	1.		1.	
TO	TH_DS_LE	TANK	QUEUE	ff_5		0.	
TO	TH_DS_HE	TANK	QUEUE	ff_6		0.	
COEF	THEATER	TANK	R-FAILS	1.0		1.0	

The user couid add similar constraints and activities for the other equipment types.

The priorities assigned to these activities for Blue and Red place them after the generation of maintenance workload by battle damage, but before the maintenance is actually performed. This means that the equipment has a chance to be used in a weapon before RAM failures are subtracted from equipment on hand. Thus, RAM failures in one period have no effect on weapon availability until the next period. The alternative—to subtract RAM failures from equipment on hand before preparing weapons for combat (i.e., before the READY activities)—would allow RAM failures to affect weapon availability in the period in which the RAM failures occur. However, it would also ensure that every equipment item that suffered a RAM failure would be unavailable for at least one full 12-hour time period.

Repair of Combat Equipment

The DIAGNOSE Activity. The DIAGNOSE activity moves equipment items from the QUEUE node to the AWP (Awaiting Parts) node of a DS Maintenance company (see Fig. 7.2), and simultaneously moves the damaged or defective component to the Light Equipment or Heavy Equipment GS Maintenance Company, as appropriate. The component movement is shown by a dashed line in the figure. (All activities that involve only components, and not equipment, are shown by dashed lines.) In addition, some of the capacity of the DS Maintenance Company is consumed. The SUPPORT records that implement these activities are as follows.

PIPE	DV_DS_LE	TANK	DIAGNOSE	rt_1	2.01	0.	2.01
FROM	DV_DS_LE	TANK	QUEUE	1.0		1.0	
TO	DV_DS_LE	TANK	AWP	1.0		1.0	
TO	GS_LE	TANK PRT	QUEUE	1.0		1.0	
COEF	ALL	DV_DS_LE	CAP	mmh_1		0.	
COEF	DV_DS_LE	TANK PRT	REORDER	–1.0		–1.0	

PIPE	DV_DS_HE	TANK	DIAGNOSE	rt_2	2.11	0.	2.11
FROM	DV_DS_HE	TANK	QUEUE	1.0		1.0	
TO	DV_DS_HE	TANK	AWP	1.0		1.0	
TO	GS_HE	TANK PRT	QUEUE	1.0		1.0	
COEF	ALL	DV_DS_HE	CAP	mmh_2		0.	
COEF	DV_DS_HE	TANK PRT	REORDER	–1.0		–1.0	
PIPE	CS_DS_LE	TANK	DIAGNOSE	rt_1	2.21	0.	2.21
FROM	CS_DS_LE	TANK	QUEUE	1.0		1.0	
TO	CS_DS_LE	TANK	AWP	1.0		1.0	
TO	GS_LE	TANK PRT	QUEUE	1.0		1.0	
COEF	ALL	ND_DS_LE	CAP	mmh_1		0.	
COEF	ND_DS_LE	TANK PRT	REORDER	–1.0		–1.0	
PIPE	CS_DS_HE	TANK	DIAGNOSE	rt_2	2.31	0.	2.31
FROM	CS_DS_HE	TANK	QUEUE	1.0		1.0	
TO	CS_DS_HE	TANK	AWP	1.0		1.0	
TO	GS_HE	TANK PRT	QUEUE	1.0		1.0	
COEF	ALL	ND_DS_HE	CAP	mmh_2		0.	
COEF	ND_DS_HE	TANK PRT	REORDER	–1.0		–1.0	
PIPE	TH_DS_LE	TANK	DIAGNOSE	rt_1	2.41	0.	2.41
FROM	TH_DS_LE	TANK	QUEUE	1.0		1.0	
TO	TH_DS_LE	TANK	AWP	1.0		1.0	
TO	GS_LE	TANK PRT	QUEUE	1.0		1.0	
COEF	ALL	ND_DS_LE	CAP	mmh_1		0.	
COEF	ND_DS_LE	TANK PRT	REORDER	–1.0		–1.0	
PIPE	TH_DS_HE	TANK	DIAGNOSE	rt_2	2.51	0.	2.51
FROM	TH_DS_HE	TANK	QUEUE	1.0		1.0	
TO	TH_DS_HE	TANK	AWP	1.0		1.0	
TO	GS_HE	TANK PRT	QUEUE	1.0		1.0	
COEF	ALL	ND_DS_HE	CAP	mmh_2		0.	
COEF	ND_DS_HE	TANK PRT	REORDER	–1.0		–1.0	

Repair times (rt_i) and maintenance man-hours (mmh_i) per repair cover the complete repair of the equipment item. (We discussed sources of data for evaluating these parameters earlier in Section 7.) However, we represent the complete repair in two steps: a DIAGNOSE activity followed by a DS REPR activity. The repair times and maintenance man-hours per repair must be split between the two activities. We can suggest no reason for preferring one split over another. Therefore, we suggest assigning half the repair time and half the maintenance man-hours per repair to each activity.

The DS REPR Activities. To complete the repair of an equipment item, the DS maintenance personnel take the equipment from the AWP node and an appropriate component from the ON HAND node (meaning components on hand), and combine them to produce an operational equipment item at the "Equipment On Hand" node of the same

echelon as the maintenance company doing the work. This activity is labeled DS REPR in Fig. 7.2.

To represent this activity realistically, we must impose a constraint to reflect the likelihood that the DS Maintenance Company has the right component on hand to repair an item of equipment. The maintenance scheme just outlined partially decouples the availability of equipment from the performance of maintenance. An equipment item is unavailable, of course, while the damaged component is identified and replaced by the DS Maintenance Company. But so long as the right replacement component is available, component repair may be deferred indefinitely without affecting the availability of the equipment item. On the other hand, if the right replacement component is not available, the equipment item must wait for the GS Maintenance Company to repair the component and return it to the DS Maintenance Company. Generally, some of the needed parts will be available and others will not.

There are detailed models of the repair process, in which the myriad different kinds of components that might be needed to repair an equipment item are all individually represented. Dyna-METRIC is one model that has been developed and used extensively at RAND.[4] If we collected the needed data about inventories, failure frequencies, and repair times of the various parts associated with an equipment item, we could use a model like Dyna-METRIC to estimate how often the needed part is available, and we could calibrate a simpler LDM representation to the Dyna-METRIC results. Imagine, then, that a detailed Dyna-METRIC simulation has been performed for a particular type of equipment, such as an M1 tank, and that we have collected the following data:

- Number of total tanks needing repair by DS Maintenance Companies in each time period (includes tanks awaiting parts and tanks newly arriving for repair);
- Number of total tank parts available at DS Maintenance Companies to make repairs in each time period; and
- Number of total tanks actually repaired in each time period.

We form two ratios from these data: (1) total tanks repaired divided by total tanks needing repair, and (2) total tank parts available to make repairs divided by total tanks needing repair. Figure 7.3 shows a hypothetical plot of these two ratios against one another. The thin solid line shows the maximum possible tanks repaired, equal to the tanks needing repair if there are sufficient parts available, but otherwise equal to the total parts available. Points

[4]For an example of an analysis that employed Dyna-METRIC, see [15].

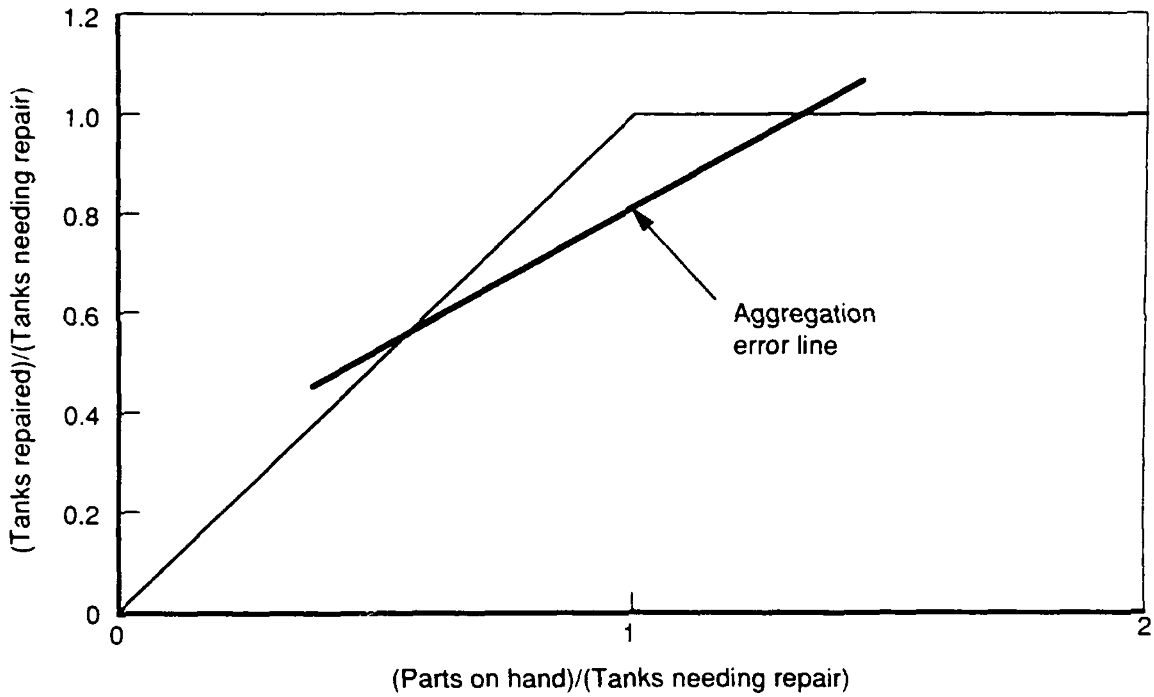

Fig. 7.3—Tanks Repaired Versus Tank Parts Available as Fractions of Tanks Needing Repair

from the detailed simulation form a cloud below the line because the right part for a particular repair will not always be available even though there may be an ample supply of the wrong parts. We cannot force an aggregate model, such as the one we are formulating here, to reproduce the cloud of points generated by a detailed simulation. But we can draw a line through the heart of the cloud of points (the thick solid line labeled "Aggregation Error Line" in Fig. 7.3) and force the aggregate formulation to produce points lying on that line whenever the ratio of parts available to tanks needing repair is in the proper range.

This is accomplished by the following condition:

$$\frac{\text{TANKS REPAIRED}}{\text{TANKS NEEDING REPAIR}} \leq \gamma + \delta \times \frac{\text{PARTS AVAIL}}{\text{TANKS NEEDING REPAIR}} \tag{7.1}$$

The coefficients in Inequality (7.1) must be obtained by fitting it to the "Aggregation Error Line" in Fig. 7.3. To implement Inequality (7.1) as a constraint in LDM, we convert it to a linear inequality by multiplying by (TANKS NEEDING REPAIR).

$$(\text{TANKS REPAIRED}) \le \gamma \times (\text{TANKS NEEDING REPAIR}) + \delta \times (\text{PARTS AVAIL}) \quad (7.2)$$

We initialize the right-hand sides of the constraint corresponding to Inequality (7.2) with the following SUPPORT records.

CONSTR	DV_DS_LE	TANK	AEL		
RHS	DV_DS_LE	TANK	AWP	γ_1	0.
RHS	DV_DS_LE	TANK PRT	ON HAND	δ_1	0.
CONSTR	DV_DS_HE	TANK	AEL		
RHS	DV_DS_HE	TANK	AWP	γ_2	0.
RHS	DV_DS_HE	TANK PRT	ON HAND	δ_2	0.
CONSTR	ND_DS_LE	TANK	AEL		
RHS	ND_DS_LE	TANK	AWP	γ_3	0.
RHS	ND_DS_LE	TANK PRT	ON HAND	δ_3	0.
CONSTR	ND_DS_HE	TANK	AEL		
RHS	ND_DS_HE	TANK	AWP	γ_4	0.
RHS	ND_DS_LE	TANK PRT	ON HAND	δ_4	0.

We call these the Aggregation Error Line (AEL) constraints. There should be one constraint for each type of equipment.

The DS Repair activities are implemented by the following SUPPORT records.

PIPE	DV_DS_LE	TANK	DS REPR	rt_5	5.01	0.	5.01
FROM	DV_DS_LE	TANK	AWP	1.0		1.0	
TO	DISCOM	TANK	ON HAND	1.0		1.0	
COEF	ALL	DV_DS_LE	CAP	mmh_5		0.	
COEF	DV_DS_LE	TANK	AEL	1.0		0.	
FROM	DV_DS_LE	TANK PRT	ON HAND	1.0		0.	
FROM	DV_DS_LE	TANK PRT	REORDER	−1.0		−1.0	
PIPE	DV_DS_HE	TANK	DS REPR	rt_6	5.11	0	5.11
FROM	DV_DS_HE	TANK	AWP	1.0		1.0	
TO	DISCOM	TANK	ON HAND	1.0		1.0	
COEF	ALL	DV_DS_HE	CAP	mmh_6		0.	
COEF	DV_DS_HE	TANK	AEL	1.0		0.	
FROM	DV_DS_HE	TANK PRT	ON HAND	1.0		0.	
FROM	DV_DS_HE	TANK PRT	REORDER	−1.0		−1.0	
PIPE	CS_DS_LE	TANK	DS REPR	rt_5	5.21	0.	5.22
FROM	CS_DS_LE	TANK	AWP	1.0		1.0	
TO	COSCOM	TANK	ON HAND	1.0		1.0	
COEF	ALL	ND_DS_LE	CAP	mmh_5		0.	
COEF	ND_DS_LE	TANK	AEL	1.0		0.	
FROM	ND_DS_LE	TANK PRT	ON HAND	1.0		0.	
FROM	ND_DS_LE	TANK PRT	REORDER	−1.0		−1.0	
PIPE	CS_DS_HE	TANK	DS REPR	rt_6	5.31	0.	5.31
FROM	CS_DS_HE	TANK	AWP	1.0		1.0	

TO	COSCOM	TANK	ON HAND	1.0		1.0	
COEF	ALL	ND_DS_HE	CAP	mmh_6		0.	
COEF	ND_DS_HE	TANK	AEL	1.0		0.	
FROM	ND_DS_HE	TANK PRT	ON HAND	1.0		0.	
FROM	ND_DS_HE	TANK PRT	REORDER	–1.0		–1.0	
PIPE	TH_DS_LE	TANK	DS REPR	rt_5	5.41	0.	5.41
FROM	TH_DS_LE	TANK	LE AWP	1.0		1.0	
TO	THEATER	TANK	ON HAND	1.0		1.0	
COEF	ALL	ND_DS_LE	CAP	mmh_5		0.	
COEF	ND_DS_LE	TANK	AEL	1.0		0.	
FROM	ND_DS_LE	TANK PRT	ON HAND	1.0		0.	
FROM	ND_DS_LE	TANK PRT	REORDER	–1.0		–1.0	
PIPE	TH_DS_HE	TANK	DS REPR	rt_6	5.51	0.	5.51
FROM	TH_DS_HE	TANK	AWP	1.0		1.0	
TO	THEATER	TANK	ON HAND	1.0		1.0	
COEF	ALL	ND_DS_HE	CAP	mmh_6		0.	
COEF	ND_DS_HE	TANK	AEL	1.0		0.	
FROM	ND_DS_HE	TANK PRT	ON HAND	1.0		0.	
FROM	ND_DS_HE	TANK PRT	REORDER	–1.0		–1.0	

The GS REPR Activities. These activities repair components at the Light Equipment and Heavy Equipment GS Maintenance Companies. They take broken components from the nodes labeled QUEUE in the (GS, LE) and (GS, HE) boxes of Fig. 7.2 and deliver them to the nodes labeled ON HAND. These activities also consume GS maintenance man-hours and take some time.

PIPE	GS_LE	TANK PRT	GS REPR	rt_3	3.01	0.	3.01
FROM	GS_LE	TANK PRT	QUEUE	1.0		1.0	
TO	GS_LE	TANK PRT	ON HAND	1.0		1.0	
COEF	ALL	GS_LE	CAP	mmh_3		0.	
PIPE	GS_HE	TANK PRT	GS REPR	rt_4	3.11	0.	3.11
FROM	GS_HE	TANK PRT	QUEUE	1.0		1.0	
TO	GS_HE	TANK PRT	ON HAND	1.0		1.0	
COEF	ALL	GS_LE	CAP	mmh_4		0.	

The Component RESUPPLY Activities. These activities move repaired components from the GS Maintenance Companies to the DS Maintenance Companies that need them. LDM will use a REORDER constraint for each type of component at each DS Maintenance Company to determine how many components are needed there. These constraints are identical in principle to the equipment REORDER constraints discussed earlier.

CONSTR	DV_DS_LE	TANK PRT	REORDER		
RHS	DV_DS_LE	TANK PRT	AUTH	1.0	1.0
RHS	DV_DS_LE	TANK PRT	ON HAND	–1.0	–1.0
RHS	DV_DS_LE	TANK PRT	RESUPPLY	–1.0	–1.0
CONSTR	DV_DS_HE	TANK PRT	REORDER		
RHS	DV_DS_HE	TANK PRT	AUTH	1.0	1.0
RHS	DV_DS_HE	TANK PRT	ON HAND	–1.0	–1.0
RHS	DV_DS_HE	TANK PRT	RESUPPLY	–1.0	–1.0
CONSTR	ND_DS_LE	TANK PRT	REORDER		
RHS	ND_DS_LE	TANK PRT	AUTH	1.0	1.0
RHS	ND_DS_LE	TANK PRT	ON HAND	–1.0	–1.0
RHS	ND_DS_LE	TANK PRT	RESUPPLY	–1.0	–1.0
CONSTR	ND_DS_HE	TANK PRT	REORDER		
RHS	ND_DS_HE	TANK PRT	AUTH	1.0	1.0
RHS	ND_DS_HE	TANK PRT	ON HAND	–1.0	–1.0
RHS	ND_DS_HE	TANK PRT	RESUPPLY	–1.0	–1.0

The component RESUPPLY activities move components from an ON HAND node at a GS Maintenance Company to an ON HAND node at one of the DS Maintenance Companies. Because they increase the supply of components at the DS Company, they make it more likely that the correct components will be available at the DS Company to repair the corresponding type of equipment. Thus there must be an entry in the appropriate AEL constraint. Finally, there is an entry in the appropriate REORDER constraint.

PIPE	DV_DS_LE	TANK PRT	RESUPPLY	tt_7	4.01	0.	4.01
FROM	GS_LE	TANK PRT	ON HAND	1.0		1.0	
TO	DV_DS_LE	TANK PRT	ON HAND	1.0		1.0	
TO	DV_DS_LE	TANK	AEL	δ_1		0.	
COEF	DV_DS_LE	TANK PRT	REORDER	1.0		1.0	
PIPE	DV_DS_HE	TANK PRT	RESUPPLY	tt_7	4.11	0.	4.11
FROM	GS_HE	TANK PRT	ON HAND	1.0		1.0	
TO	DV_DS_HE	TANK PRT	ON HAND	1.0		1.0	
TO	DV_DS_HE	TANK	AEL	δ_2		0.	
COEF	DV_DS_HE	TANK PRT	REORDER	1.0		1.0	
PIPE	ND_DS_LE	TANK PRT	RESUPPLY	tt_8	4.21	0.	4.21
FROM	GS_LE	TANK PRT	ON HAND	1.0		1.0	
TO	ND_DS_LE	TANK PRT	ON HAND	1.0		1.0	
TO	ND_DS_LE	TANK	AEL	δ_3		0.	
COEF	ND_DS_LE	TANK PRT	REORDER	1.0		1.0	
PIPE	ND_DS_HE	TANK PRT	RESUPPLY	tt_8	4.31	0.	4.31
FROM	GS_HE	TANK PRT	ON HAND	1.0		1.0	
TO	ND_DS_HE	TANK PRT	ON HAND	1.0		1.0	
TO	ND_DS_HE	TANK	AEL	δ_4		0.	
COEF	ND_DS_HE	TANK PRT	REORDER	1.0		1.0	

We discussed sources of data for evaluating the transportation times (denoted tt_i) earlier in this section.

Equipment RESUPPLY Activities

The equipment RESUPPLY activities replace equipment that has been lost from any echelon by moving replacement equipment forward from higher echelons. The SUPPORT records are as follows.

PIPE	COSCOM	TANK	RESUPPLY	tt_9	5.01	0.	5.01
FROM	THEATER	TANK	ON HAND	1.0		1.0	
TO	COSCOM	TANK	ON HAND	1.0		1.0	
COEF	COSCOM	TANK	REORDER	1.0		1.0	
PIPE	DISCOM	TANK	RESUPPLY	tt_{10}	5.11	0.	5.11
FROM	COSCOM	TANK	ON HAND	1.0		1.0	
TO	DISCOM	TANK	ON HAND	1.0		1.0	
COEF	DISCOM	TANK	REORDER	1.0		1.0	
PIPE	BRIGADE	TANK	RESUPPLY	tt_{11}	5.21	0.	5.21
FROM	DISCOM	TANK	ON HAND	1.0		1.0	
TO	BRIGADE	TANK	ON HAND	1.0		1.0	
COEF	BRIGADE	TANK	REORDER	1.0		1.0	

MAINTENANCE SUPPORT FOR CSS UNITS

In the formulations in Sections 5 and 6 of the ammunition and POL distribution systems, we identified several kinds of CSS units. Failure of equipment possessed by these units imposes a workload on the maintenance units (which are themselves CSS companies). If that workload is not processed, the CSS companies that generate it will be unable to perform at full capacity.

One way to represent these phenomena is to introduce activities like the RAM failure activities, and the DS and GS repair activities defined for combat equipment. Figure 7.4 illustrates the structure we formulate in the following paragraphs. Table 7.3 shows the activities involved in providing maintenance support to one kind of CSS unit: the GS Ordnance Company that handles ammunition in the ammunition distribution system. These activities should be replicated for each kind of CSS unit represented in the LDM input data. The CSS units identified in Sections 5 and 6 operate to the rear of the division area, so we do not define activities that send workload to the Divisional Light or Heavy Equipment DS Maintenance Companies.

The RAM FAILS activities for CSS units, like their counterparts for combat equipment, calculate the amount of equipment that fails per time period. Because the equipment items owned by CSS units are not explicitly represented, we substitute the

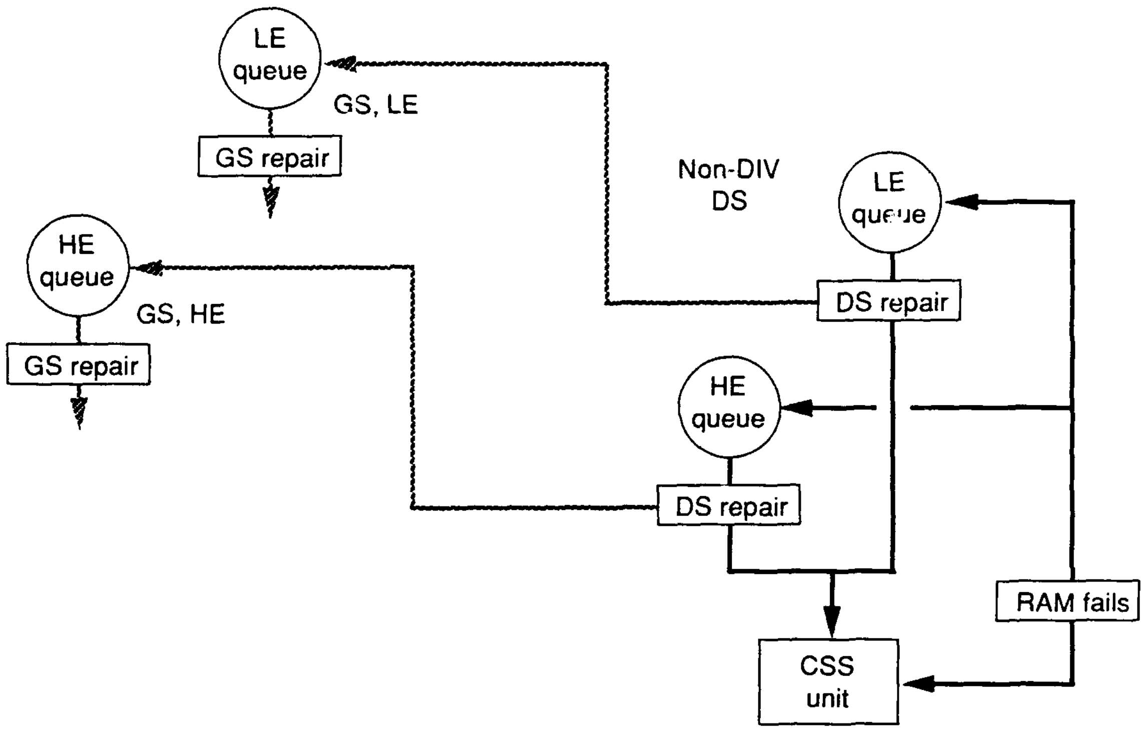

Fig. 7.4—Maintenance Support of CSS Units

Table 7.3

Activities for Maintenance Support of GS Ordnance Company

ALL	GS ORD	RAM FAIL
ND_DS_LE	GS ORD	DS REPR
ND_DS_HE	GS ORD	DS REPR
GS_LE	GS ORD	GS REPR
GS_HE	GS ORD	GS REPR

fraction of the CSS unit's design capacity that will be lost per time period because of RAM failures of equipment.

The DS REPR activities represent the repair of failed equipment at the Nondivisional DS Maintenance Company. During the repair of equipment, workload is generated for GS Maintenance units. We do not explicitly represent the components used in the repair of CSS

equipment, so there is no need to separate a DIAGNOSE activity from the DS REPR activity and no need to introduce a RESUPPLY activity for components.[5]

In the discussion of "Maintenance and Resupply of Combat Equipment," we began by defining REORDER constraints for equipment and ended with the equipment RESUPPLY activities. These are unnecessary for CSS units because there is no mechanism for losing CSS equipment. It is all repaired and returned to the unit. If the user were to introduce a source of loss—e.g., if a fraction less than one of the repaired CSS equipment were returned to the unit—then he would have to introduce a resupply mechanism similar to that for combat equipment.

Generating Maintenance Workload

The generation of workload by a GS Ordnance Company can be represented by the following records. First, we specify the fraction of the unit's capacity that is lost per time period because of RAM failures of its equipment.

CONSTR	ALL	GS ORD	R-FAILS		
RHS	ALL	GS ORD	UNIT	ff_7	0.

For example, if a Blue unit lost 2 percent of its capacity in each 12-hour period (assuming the equipment were lost, and not simply repaired and returned to the unit), then one would set $ff_7 = 0.02$.

No book of planning factors currently contains estimates of ff_7 for various kinds of CSS units. To implement the scheme described here, the user must estimate this parameter himself. One possible way to estimate ff_7 is as follows.

- Estimate the capacity of the CSS unit with its initial inventory of equipment. Let that capacity be C_0.
- Determine the average number of each item of equipment that will fail per day in wartime. Such data exist for peacetime, and they can be scaled to account for increased wartime usage.
- Reduce the CSS unit's equipment inventory by a convenient number of days' worth of equipment failures. Let the number of days' worth chosen be N.

[5]Nothing prevents us from including the effects of components on the repair of CSS equipment. We choose to exclude it merely to illustrate a simpler formulation of the maintenance process.

- Estimate the capacity of the CSS unit with the reduced inventory of equipment. Refer to [2] for some ideas on how this can be done. Let the reduced capacity, following N days of equipment failures without replacement, be C_N.

Then the formula for ff_7 is as follows:

$$ff_7 = \frac{C_0 - C_N}{2 \times N \times C_0} \tag{7.3}$$

The factor "2" in the denominator adjusts for the fact that there are two 12-hour LDM time periods per day.

Next, we define the RAM FAIL activity that reduces the available capacity of units of this kind, and adds workload to both the light and heavy equipment maintenance queues of the Nondivisional DS Maintenance Company.

PIPE	ALL	GS ORD	RAM FAIL	0.	1.41	0.	1.41
FROM	ALL	GS ORD	UNIT	1.0		1.0	
TO	ND_DS_LE	GS ORD	QUEUE	ff_8		0.	
TO	ND_DS_HE	GS ORD	QUEUE	ff_9		0.	
COEF	ALL	GS ORD	R-FAILS	1.0		1.0	

The priorities for these activities call for their rates to be calculated at the same point in the calculations as the RAM FAIL activities for equipment items. Thus, the CSS workload will compete with the combat equipment workload for maintenance capacity.

Repair Activities

DS REPR Activities. Each DS REPR activity moves CSS equipment from the maintenance queues (labeled QUEUE in Fig. 7.4) at the DS Maintenance Company back to the CSS unit. It also generates workload for a GS Company and consumes some of the capacity of the DS Company. The following are the SUPPORT records that implement these activities.

PIPE	ND_DS_LE	GS ORD	DS REPR	rt_{12}	5.21	0.	5.21
FROM	ND_DS_LE	GS ORD	QUEUE	1.0		1.0	
TO	ALL	GS ORD	UNIT	1.0		1.0	
TO	GS_LE	GS ORD	QUEUE	1.0		1.0	
COEF	ALL	ND_DS_LE	CAP	mmh_7		0.	
PIPE	ND_DS_HE	GS ORD	DS REPR	rt_{12}	5.31	0.	5.31
FROM	ND_DS_HE	GS ORD	QUEUE	1.0		1.0	
TO	ALL	GS ORD	UNIT	1.0		1.0	

TO	GS_HE	GS ORD	QUEUE	1.0	1.0
COEF	ALL	ND_DS_HE	CAP	mmh_8	0.

The priorities of these activities call for their rates to be calculated at the same point in the simulation cycle as the DS REPR activities for combat equipment.

GS REPR Activities. Each GS REPR activity merely empties a maintenance queue at the GS Company and consumes some of that company's capacity. The following SUPPORT records implement these activities.

PIPE	GS_LE	GS ORD	GS REPR	0.0	3.01	0.	3.01
FROM	GS_LE	GS ORD	QUEUE	1.0		1.0	
COEF	ALL	GS_LE	CAP	mmh_9		0.	
PIPE	GS_HE	GS ORD	GS REPR	0.0	3.11	0.	3.11
FROM	GS_HE	GS ORD	QUEUE	1.0		1.0	
COEF	ALL	GS_HE	CAP	mmh_{10}		0.	

There is no need to specify durations for these activities because they do not produce any resources (note the absence of any TO records). Because these activities produce nothing, they do not affect how fast CSS equipment is repaired and returned to CSS units. However, because these activities consume maintenance capacity, they interfere with the ability of the GS Companies to repair components of combat equipment. The priorities of these activities call for their rates to be calculated at the same point in the simulation cycle as the GS REPR activities for combat equipment.

OTHER ARMY MAINTENANCE WORKLOADS

We have not mentioned many kinds of Army units that will be deployed to the NATO theater of operations. These include supply units, military police, engineers, medical units, and many others. All of these units will require maintenance support.

We have considered three approaches for dealing with the maintenance support for these units. First, we can ignore it. This amounts to assuming that the maintenance required by these units can be deferred indefinitely, with no effect on the Army's combat performance. A simulation based on this approach will yield the most optimistic results, for it makes the greatest amount of maintenance available to users of maintenance represented in LDM.

Second, we can estimate the maintenance man-hours per day (both light and heavy equipment maintenance man-hours, and both DS and GS) that these units will consume, and subtract them from the available capacity. This gives these units first priority for

maintenance, leaving the units explicitly represented in LDM to compete for the remaining maintenance capacity. A simulation based on this approach will yield the most pessimistic results, for it makes the least amount of maintenance capacity available to users of maintenance represented in LDM.

The third approach is an intermediate one between the first two. We can make separate estimates of the average daily maintenance man-hours consumed by users of maintenance that are represented in LDM and by users of maintenance that are not represented. Then we can inflate all the maintenance consumption factors of the represented users so that they include a pro rata share of maintenance use by unrepresented users.

Although the third approach might appear more likely to yield accurate results than either of the other two approaches, it is actually less desirable than a combination of the first two approaches. We recommend running the simulation twice, once with no adjustment for unrepresented units (approach one), and once more with maintenance capacity set aside for the use of unrepresented units before the simulation even begins (approach two). The results from the two simulations should bracket the "true" results. If there is little difference between the two simulations—either because both have severe maintenance shortages or because neither does—the conclusions one draws about maintenance will be robust. We cannot say whether a simulation using the third approach is optimistic or pessimistic; conclusions drawn from such a simulation may well not be robust.

On the other hand, simulations using approaches one and two may differ substantially. This situation may arise if the maintenance man-hours demanded by unrepresented units are a large fraction of the total maintenance demanded by all units. In this event, either some of the unrepresented units must be added to LDM, or a separate study of maintenance must be performed to provide a reasonable basis for allocating supplies and capacity between represented and unrepresented units.

Appendix A
LDM'S COMBAT MODULE

The purpose of LDM's combat module is to estimate, for each simulated time period:

- Measures of the combat performance of the forces that each side is able to field in that time period. These measures are FLOT movement and weapon systems engaged and hit on each side.
- Workloads that combat imposes on the support system. These workloads are losses, consumption, and battle damage to resources that the support system must replace or repair.

The combat module requires as inputs the numbers of each type of weapon available to each side's combat forces; these quantities are calculated by LDM's support module. It also requires various tabular information that remains constant for all time periods (found in the ATTRITION file) and a few parameters that may change from one period to the next (found in the TIME_PHASE file).

ENGAGED WEAPON SYSTEMS

Key inputs to the combat module are the numbers of each weapon on each side that are available to the combat forces. These quantities are calculated by the support module from the resources available to those forces. (In the test case, these are the READY activities, such as BRIGADE .. TANK .. READY.) For example, for a tank to be available as a weapon to the combat forces, those forces must have on hand not only the piece of equipment known as a tank but also a tank crew, tank main gun ammunition, and so forth. Let:

$AWPN_{ni}$ = number of weapons of type n available to side i (i=1 for Blue, i=2 for Red)

LDM has input parameters for each time period that specify what fractions of the Blue and Red forces engage in combat. These parameters, one each for Blue and Red, may be changed for each simulation cycle. They are found in the TIME records in the TIME_PHASE input file (see [3], Chapter. 7). Unengaged forces include forces in reserve, plus any forces that have broken contact with the enemy in order to maneuver or to retreat to a prepared position. They also include forces whose immediate opposition has broken contact.

Denote these fractions by:

λ_i = fraction of available weapons that will engage on side i (i=1 for Blue, i=2 for Red)

Then the numbers of weapons engaged will be:

$$EWPN_{ni} = \lambda_i \times AWPN_{ni} \tag{A.1}$$

THE COMBAT WORTH FUNCTION

In LDM, force is measured by a "combat worth" function. This is a linear function of the engaged numbers of weapons of the various types. The coefficients for the different weapons are found in the ATTRITION file (see [3], Chapter 4). Let:

CW_{ni} = combat worth coefficient for weapons of type n on side i (i=1 for Blue, i=2 for Red)

Then the engaged combat worth on each side is calculated as:

$$CWTOT_i = \sum_n \{CW_{ni} \times EWPN_{ni}\} \tag{A.2}$$

DISTRIBUTION OF COMBAT WORTH

Blue and Red engaged forces are not distributed uniformly across the theater. One Blue division may be facing a Red force several times its own strength, while another Blue division may enjoy a substantial superiority over its local opponent. To represent the nonuniform distribution of force, LDM spreads the Blue and Red engaged forces across a number of combat worth ratio categories (ratio of Blue to Red combat worth). We have assumed that the combat worth ratio follows a log-normal distribution; this distribution appears to fit data from both CEM and FORCEM[1] quite well.

According to this assumption, there should be two parameters—say, "m" and "s"—such that the fraction of the overall Blue force engaged at local force ratios less than 'ρ' (the ratio of Blue to Red combat worth in the local engagement) is:

$$F(\rho) = \Phi\left(\frac{\log \rho - m}{s}\right) \tag{A.3}$$

where the function 'Φ' is the cumulative normal distribution with mean 0.0 and variance 1.0.

[1]CEM (Concepts Evaluation Model) and its intended successor FORCEM (Force Evaluation Model) are large theater simulations used in a variety of studies by the U.S. Army Concepts Analysis Agency (CAA). We have used both of these models at different times as sources of calibration data for LDM.

Under this assumption, it turns out that the fraction of the engaged Red combat worth is also distributed log-normally. (This symmetry between Blue and Red is one reason for selecting the log-normal distribution.) The value of the standard deviation "s" is the same for the two sides, but the Blue and Red distributions have somewhat different values for the parameter "m." Indeed:

$$m_1 = \log \frac{CWTOT_1}{CWTOT_2} + \frac{s^2}{2} \qquad (\text{side } 1 = \text{Blue}) \tag{A.4a}$$

$$m_2 = \log \frac{CWTOT_1}{CWTOT_2} - \frac{s^2}{2} \qquad (\text{side } 2 = \text{Red}) \tag{A.4b}$$

In each time period, LDM calculates a new distribution of engaged forces across combat ratios. The parameter "s" is input anew at each time period on the TIME records in the TIME_PHASE input file, along with the fractions λ_i of the available weapon systems that are engaged.

ENGAGEMENT CATEGORIES

To represent the log-normal distribution of combat worth ratio, LDM spreads each side's forces among the 16 combat worth ratio intervals shown in Table A.1. These inputs are found in the ATTRITION file, key word CATEGORIES.

Table A.1

Combat Worth Ratio Intervals

Interval	Ratio (Blue/Red)		Interval	Ratio (Blue/Red)	
No.	From	To	No.	From	To
1.	0.0	0.1	9.	1.0	1.5
2.	0.1	0.15	10.	1.5	2.0
3.	0.15	0.2	11.	2.0	3.0
4.	0.2	0.25	12.	3.0	4.0
5.	0.25	0.333	13.	4.0	5.0
6.	0.333	0.5	14.	5.0	6.667
7.	0.5	0.667	15.	6.667	10.0
8.	0.667	1.0	16.	10.0	—

Forces engaged in any of the combat worth ratio intervals can be in one of three postures:

1. Blue attack – Red defend
2. Red attack – Blue defend
3. Static

Posture data are input in the form of a 3×16 table, whose entries we denote by POS_{jk} (ATTRITION file, key word POSTURE).

POS_{jk} = ratio of forces engaged in posture j and combat worth ratio category k, to all forces engaged in combat worth ratio interval k

For each ratio category k, we intend that:

$$POS_{1k} + POS_{2k} + POS_{3k} = 1 \tag{A.5}$$

However, LDM does not check for this. Hence it is the user's responsibility to do so. The posture data are established during calibration. (See Sections 2 and 3 in this Note.)

Using the 3×16 table, and the log-normal distributions of Blue and Red combat worth over the combat worth ratio categories, LDM calculates two *engagement category tables*—one each for Blue and Red. The calculation is as follows. Let:

$F_i(\rho)$ = cumulative distribution of side i's combat worth, as a function of the ratio of the Blue to Red combat worth. This is a log-normal distribution (see Equation (A.3)), with the appropriate mean for side i (Equation (A.4a) or (A.4b)) and standard deviation "s."

ρ_0 = 0

ρ_k = upper limit on the k^{th} combat worth ratio interval, as shown in Table A.1, where $1 \leq k \leq 16$.

Then define the engagement distribution table "E" according to the following formula:

$$E_{ijk} = POS_{jk} \times [F_i(\rho_k) - F(\rho_{i-1})] \tag{A.6}$$

The first index in table "E" denotes the side, with i=1 denoting Blue and i=2 denoting Red. For each side, "E" is a table of probabilities, *not* a table of the amounts of combat worth in each cell of the table. That is, assuming that the posture table POS_{jk} satisfies Equation (A.5), then for each side i:

$$\sum_j \sum_k E_{ijk} = 1 \qquad (A.7)$$

CALCULATING FLOT MOVEMENT AND ATTRITION

FLOT movement data are entered as a $2 \times 3 \times 16$ table (ATTRITION file, key word MOVEMENT). Let:

M_{ijk} = movements of side i when engaged in posture j in interval k of combat worth ratios.

Then it is a straightforward procedure to calculate the average movement of either side as:

$$MAVG_i = \sum_j \sum_k \{E_{ijk} \times M_{ijk}\} \qquad (A.8)$$

LDM reports the Blue movement as FLOT movement and ignores Red movement entirely. (It is calculated, but it is never output.)

Similarly, attrition data for each weapon are entered as a $2 \times 3 \times 16$ table (ATTRITION file, key word ATTRITION). Let:

H_{nijk} = fraction of engaged weapons that suffer hits, for weapons of type n, on side i, in posture j and interval k of combat worth ratios.

Then the number of each weapon type that is hit is calculated as:

$$HITS_{ni} = EWPN_{ni} \times \sum_j \sum_k \{E_{ijk} \times H_{nijk}\} \qquad (A.9)$$

where $EWPN_{ni}$ was defined earlier (in Equation (A.1)) as the number of weapons of type "n" engaged on side "i."

CALCULATING COMBAT LOSS FUNCTIONS

The combat loss functions are defined in the CBT_LOSS data, found in the ATTRITION file (Chapter 4 of the LDM Users' Manual). LDM uses these functions to estimate the workloads that the combat module passes to the support module. Let:

CE_{fni} = coefficient for combat loss function f of *engaged* weapons of type n on side i.

CH_{fni} = coefficient for combat loss function f of *hit* weapons of type n on side i.

Each combat loss function "f" is used to calculate a quantity whose name appears on a DEP record. The equation is:

$$DEP_{fi} = \sum_{n} \{CE_{fni} \times EWPN_{ni}\} + \sum_{n} \{CH_{fni} \times HITS_{ni}\} \qquad (A.10)$$

These quantities are passed to the support module, to be discussed in Appendix B.

Appendix B
LDM'S SUPPORT MODULE

Each time LDM's support module is exercised, it simulates the operation of the support system for one 12-hour time period. It accepts as inputs the amounts of resources available at the end of the previous time period, as well as amounts of resources that were lost or consumed in combat during the current time period. Given this information, plus the amounts of resources entering the theater, it does the following:

1. First, it calculates the resources that will be available during the current period. This calculation involves little more than multiplying a vector of resource quantities by a matrix that we call the *resource matrix.*
2. Then it calculates the rates at which the various support activities (e.g., maintenance, transportation) occur and how much of the available resources they consume, produce, or otherwise modify. This calculation involves finding a feasible solution to a set of linear inequalities, one for each resource. Each inequality forbids more of the corresponding resource to be consumed than is available during the current time period. The variables in these inequalities are the rates of the various support activities. We call the coefficient matrix for this system of inequalities the *activity matrix.*

As a by-product, this process also yields the resources that will be available at all echelons at the end of the time period.

In Appendix B, we discuss how LDM builds the activity matrix and the resource matrix, and how it performs the calculations just outlined.

THE ACTIVITY AND RESOURCE MATRICES

The activity matrix has a row for each resource and a column for each activity.[1] Likewise, the resource matrix has a row for each resource, but each of its columns also corresponds to a resource, so it is a square matrix. There are separate activity and resource matrices for Blue and Red.

[1] In LDM, resources and activities are identified by three eight-character words. Our convention is to use the three words as, respectively, the *location*, *generic name*, and *status* of the resource. For example, a resource might be tank ammunition (the generic name) on hand (the status) at the COSCOM (location). We would give this resource the name COSCOM .. TANK AMM .. ON HAND. An activity might be transportation of tank ammunition from COSCOM to DISCOM, which we would name COSCOM .. TANK AMM .. RESUPPLY.

We denote by a_{ij} the coefficient in row i and column j of the activity matrix. One can interpret a_{ij} as the amount of the resource corresponding to row i that is consumed by one unit of the activity corresponding to column j. The choice of a unit for the activity is arbitrary, but one choice is usually more natural than others. For example, if the activity is DS repair of tanks at DISCOM, the appropriate unit of activity would be the repair of a single tank. A coefficient a_{ij} will be negative whenever row i represents a resource that is produced by activity j, because production is equivalent to negative consumption.

We denote by r_{ik} the coefficient in row i and column k of the resource matrix. It is hard to state a general interpretation of these coefficients. However, as an example, suppose that the resource corresponding to row i is the number of medical personnel available to work at DISCOM. Also suppose that the resource corresponding to column k is the medical man-hours available at DISCOM. Then the coefficient r_{ik} would be the number of man-hours per simulated time period that each medical person could provide.

LDM assumes that every coefficient in the activity matrix is zero, unless otherwise specified. It assumes that, unless otherwise specified, the coefficients on the main diagonal of the resource matrix have the value 1.0, but that coefficients off the main diagonal are zero.

Data for the nonzero coefficients for matrices are contained in the SUPPORT files. These files (of which there may be one or more) contain groups of associated records. Each group starts with a STOCK, CONSTR, or PIPE record. If the group starts with STOCK or CONSTR, it includes all RHS records immediately following. There may be zero RHS records, or one, or several. If the group starts with PIPE, it includes all immediately following FROM, TO, and COEF records. The following are examples of SUPPORT records that contain all the different kinds of data from which coefficients are obtained.

```
123456789_123456789_123456789_123456789_123456789_123456789_123456789_
CONSTR  COSCOM  TRCK HRS  AVAIL
 RHS    COSCOM  TRUCK     ON HAND   12.0            12.0
PIPE    DISCOM  TANK AMM  RESUPPLY  12.0      15.3  12.0      15.3
 FROM   COSCOM  TANK AMM  ON HAND   1.0             1.0
 TO     DISCOM  TANK AMM  ON HAND   1.0             1.0
 FROM   DISCOM  TANK AMM  REORDER   1.0             1.0
 COEF   COSCOM   ORD HRS  AVAIL     0.01419         0.01419
 COEF   COSCOM  TRCK HRS  AVAIL     0.12            0.12
 COEF   COSCOM  DRVR HRS  AVAIL     0.24            0.24
123456789_123456789_123456789_123456789_123456789_123456789_123456789_
```

The text in columns 9–48 identifies the columns and rows of the matrices in which the coefficients belong, while the values of the coefficients are calculated from the data in columns 39–46 (for Blue) and columns 55–62 (for Red). The data in columns 47–54 and 63–70 of a PIPE record identify the Blue and Red priority of the activity defined by its group of records. As explained later in Appendix B, the priority governs the order in which the activity rates are calculated.

COEFFICIENTS FROM STOCK .. RHS AND CONSTR .. RHS RECORDS

A group of SUPPORT records that begins with STOCK or CONSTR supplies coefficients for the resource matrix only. The STOCK or CONSTR record identifies which column of the matrix in which the coefficients should be placed, and each RHS record specifies a row and the coefficient values. LDM processes these groups in the following steps.

1. LDM reads the STOCK or CONSTR record and locates (or, if necessary, creates, a resource with the name given on that record. In the preceding CONSTR record, the resource is named COSCOM .. TRCK HRS .. AVAIL. If we suppose that it is the k^{th} resource, the data on the following RHS record will go in column k of the resource matrix.
2. For each RHS record that follows, LDM will locate (or create) a resource with the name on that record (COSCOM .. TRUCK .. ON HAND in the sample RHS record). Suppose that row i corresponds to that resource. The numbers in the RHS record are then added to the coefficient in row i and column k (i.e., r_{ik}). The first of the numbers in the RHS record (columns 39–46)—12.0—is added to Blue's resource matrix; the second number (columns 55–62)—in this case also 12.0—is added to Red's resource matrix.

COEFFICIENTS FROM PIPE .. FROM .. TO .. COEF RECORDS

Network Structure of the Support System

The support structure in LDM can be represented, in large part, as a network. Figure B.1 shows the part of the network for the test case that represents activities affecting supplies. The support structure contains a duplicate of this network for each type of supply simulated in the test case, including tank ammunition, artillery ammunition, and other ammunition. (The only supply type in the test case is ammunition.) Each node in the network represents a stock of some resource. Each link represents an activity that transforms the resource represented by the origin node to the resource represented by the destination node.

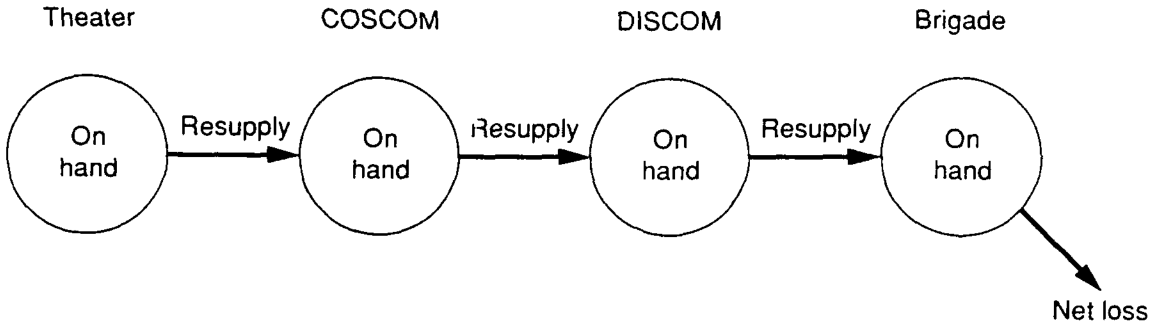

Fig. B.1—Activity Network for Supplies

To illustrate, consider the RESUPPLY link in Fig. B.1 from the node ON HAND at COSCOM to the node ON HAND at DISCOM. The node ON HAND at COSCOM represents the amount of a given type of ammunition available at the COSCOM. The link represents the transportation activity that moves ammunition from COSCOM to DISCOM. In the preceding SUPPORT records, the PIPE group defines this activity for the ammunition type TANK AMM; the activity is named DISCOM .. TANK AMM .. RESUPPLY. The first FROM record and the TO record identify the origin (COSCOM .. TANK AMM .. ON HAND) and destination (DISCOM .. TANK AMM .. ON HAND) nodes of the link.

Various considerations cannot be shown conveniently in these networks. These include the capacities of links and limitations on the amounts of resources one wishes to allow to accumulate at the various nodes. In the preceding example, the COEF records specify that the movement of a unit of ammunition from COSCOM to DISCOM consumes various amounts of supply personnel hours, truck hours, and driver hours. If any of these resources are scarce, that will limit the amount of ammunition that can be transported.

Time Delays and the Pipeline Equations

To simulate time delays, LDM treats each link of the support system network as a pipeline, in which stocks of a resource can be held for a time before delivery. Therefore, both a flow and a stock of the resource are associated with the link. (A node has only a stock.) The time required for the resource to traverse the pipeline is represented by allowing only part of the stock to exit the pipeline during the current time step and withholding the rest for later steps. The fraction withheld is adjusted so that it takes the desired average time for the resource to pass through the pipeline. However, some of the resource traverses the pipeline very quickly, and some passes through only after a very long delay.

For mathematical convenience, we assume that the time required to traverse the pipeline has an exponential distribution. In this case, the rate at which the resource flows out of the pipeline at any instant will be a fixed proportion of the amount of the resource in the pipeline at that instant. Let:

R = rate in units per hour at which resource enters pipeline (assumed constant);
τ = average time in hours for resource to traverse pipeline;
x(t) = quantity of resource in the pipeline at time t.

Then it is easy to calculate the amount of the resource in the pipeline at time t:

$$x(t) = x(0) \times \exp(-t / \tau) + Rt \times [(\tau / t) \times (1 - \exp(-t / \tau))] \tag{B.1}$$

The total amount of resource that flows from the pipeline between times 0 and t is:

$$\text{OUTFLOW} = x(0) \times (1 - \exp(-t / \tau)) + Rt \times [1 - (\tau / t) \times (1 - \exp(-t / \tau))] \tag{B.2}$$

Note that the two equations are linear in x(0) (the amount of the resource initially in the pipeline) and Rt (the total amount of the resource that enters the pipeline between time 0 and t). Given any time t, one can calculate both the pipeline content at time t and the amount of resource delivered by the pipeline from time 0 through t, from only a small amount of information—namely, the average transit time τ, the entry rate R (assumed constant between time 0 and t), and the pipeline content at time 0.

The amount of the resource that enters the pipeline during a specified time period is a reasonable measure of the rate of the activity represented by that pipeline. Thus Rt in Equations (B.1) and (B.2) can be considered an activity rate; the coefficients of Rt in these equations will appear in the column of the activity matrix corresponding to that activity. Similarly, x(0) is the amount of the resource in the pipeline at the start of the period; the terms involving x(0) in Equations (B.1) and (B.2) determine the amount of this quantity that becomes available for use by other activities during this time period. Thus the coefficients of x(0) in these equations will appear as coefficients in the resource matrix.

Coefficients from PIPE Records

A PIPE record in a SUPPORT file begins the definition of an activity and its associated pipeline. When LDM encounters a PIPE record, it locates—or, if necessary, creates—both an activity and a resource. Both the activity and the resource have the name that appears in the PIPE record (DISCOM .. TANK AMM .. RESUPPLY in the preceding example). The

resource represents the quantity held temporarily in the pipeline, which is calculated by Equation (B.1). The rate of this activity measures the amounts of one or more resources (identified on FROM records) that enter the pipeline during one simulated time period, which corresponds to the factor Rt in Equations (B.1) and (B.2).

When it encounters the PIPE record, LDM does the following:

1. It locates or creates a resource with the name in the PIPE record, and its corresponding row k of the activity and support matrices.
2. It locates or creates an activity with the name in the PIPE record, and its corresponding column j of the activity matrix.
3. It subtracts the coefficient of Rt in Equation (B.1) from row k, column j, of the activity matrix—i.e.:

   $$a_{kj} = a_{kj} - [(\tau / t) \times (1 - \exp(-t / \tau))] \ .$$

   The value of τ in this equation is taken from columns 39–46 for Blue and columns 55–62 for Red. The value of t is 12 hours, which is the duration of each simulated time period in LDM. The coefficient is subtracted rather than added because, according to our convention, a negative coefficient in the activity matrix corresponds to the production of a resource by the activity. In this instance, the activity increases the amount of the resource in the pipeline—i.e., "produces" the resource.

4. It adds the coefficient of x(0), less 1, to row k, column k, of the resource matrix. That is, set:

   $$r_{kk} = r_{kk} + [\exp(-t / \tau) - 1.0]$$

   (The reason for subtracting 1.0 is that LDM initializes the diagonal elements of the resource matrix to 1.0. Subtracting 1.0 in the equation compensates for this.)

If τ equals zero for both Blue and Red, steps 1, 3, and 4 are omitted. This is because the quantity in the pipeline would always be zero, so there is no need to keep track of it explicitly.

Coefficients from TO Records

A TO record identifies a resource to be delivered by the pipeline defined by the most recent PIPE record. That is, this resource type is a recipient of the OUTFLOW calculated by Equation (B.2). This OUTFLOW has two terms, one proportional to x(0) and the other proportional to Rt. The first term will contribute a coefficient to the resource matrix, while the second will contribute a coefficient to the activity matrix. When LDM encounters the TO record, it does the following:

0. It will have retained the column index j that corresponds to the activity named on the associated PIPE record. It will also have retained the index k of the resource created to represent the content of that pipeline. These indexes will be used to process the TO data.
1. It locates or creates a resource with the name in the TO record, and its corresponding row i in the activity and support matrices.
2. It adds the coefficient of Rt in Equation (B.2) to row i, column j, of the activity matrix. However, it first multiplies it by the numerical data in the TO record (the number in columns 39–46 for Blue, and columns 55–62 for Red). This number allows one to specify what fraction of the outflow consists of this resource.[2] Denote the number in the TO record by "p." Then:

$$a_{ij} = a_{ij} + p \times [1 - (\tau / t) \times (1 - \exp(-t / \tau))]$$

3. It adds the coefficient of x(0) to row i, column k, of the resource matrix. Again, it first multiplies it by the numbers in the TO record (in columns 39–46 for Blue and columns 55–62 for Red). That is:

$$r_{ik} = r_{ik} + p \times (1 - \exp(-t / \tau))$$

If τ equals zero for both Blue and Red, step 3 is omitted, because no resource k will have been defined when processing the associated PIPE record. In this case, the expression for a_{ij} simplifies to the following:

$$a_{ij} = a_{ij} + p$$

[2]Not all of the outflow from a pipeline must consist of a single resource. The outflow can consist of a mix of two, three, or more different resources. However, the different resources will flow from the pipeline in fixed proportions. Or, one need not identify *any* outflow resource (i.e., omit all TO records associated with a PIPE record). In this case, resources that enter the pipeline will simply disappear from the simulation.

Coefficients from FROM and COEF Records

Each FROM or COEF record provides a single coefficient to each of Blue's and Red's activity matrices.[3] These records are processed as follows:

0. LDM will have retained the column index j that corresponds to the activity named on the associated PIPE record. This index will be used to process the FROM or COEF data.
1. It locates or creates a resource with the name in the FROM or COEF record, and its corresponding row i in the activity matrix.[4]
2. It adds the number in columns 39–46 of the FROM or COEF record to row i, column j, of Blue's activity matrix; it adds the number in columns 55–62 to row i, column j, of Red's activity matrix. If "p" is the number in question, the activity matrix coefficient becomes:

$$a_{ij} = a_{ij} + p$$

SUPPORT MODULE CALCULATIONS

LDM's support module calculates the resources available to the various support activities in each simulated time period, and the rates at which the support activities occur. The calculation is done in the following four steps.

Step 1: Calculate Inherited Resources

LDM first calculates the amount of each resource inherited from the previous period. For "constraint" resources, this quantity is always zero, because unused "constraint" resources are not carried forward from one period to the next. Quantities for "stock" resources are taken to be the amount remaining at the end of the previous simulated time period for every period but the first. They are taken to be zero in the first period.

$$\mathrm{INHERIT}_i(P) = \begin{cases} \mathrm{REMAIN}_i(P-1) & \text{if i is a "stock" resource} \\ 0 & \text{if i is a "constraint" resource} \end{cases} \tag{B.3}$$

[3]LDM treats FROM and COEF records exactly the same. We use FROM records for entries that correspond to origin nodes for pipelines; we use COEF records for entries that correspond to neither origin nor destination nodes.

[4]If LDM were processing the SUPPORT records in the example at the beginning of Appendix B, it would have encountered this resource name before, on the CONSTR record. It would be unnecessary to create a new resource when encountering the name again. However, if the two occurrences of the name were spelled differently, LDM would not announce an error; rather it would obediently create two resources. The effect on simulation results is unpredictable.

where:

$INHERIT_i(P)$ = amount of resource i inherited for period P;

$REMAIN_i(P-1)$ = amount of resource i remaining from period P–1.

Step 2: Add Resources from Outside the Simulation

Next LDM adds quantities of resources from outside the simulation.

$$INITIAL_i(P) = INHERIT_i(P) + EXOG_i(P) \tag{B.4}$$

where:

$INITIAL_i(P)$ = amount of resource i on hand at the start of period P.

$EXOG_i(P)$ = amount of resource i brought in from outside the simulation for period P (from the TIME_PHASE file; see [3], Chapter 7).

Step 3: Apply the Resource Matrix

The next step is to apply the resource matrix to the initial resource quantities:

$$AVAIL_i(P) = \sum_k (INITIAL_k(P) \times r_{ki}) \tag{B.5}$$

where:

$AVAIL_i(P)$ = amount of resource i available for use by the activities during the current simulation cycle.

Step 4: Compute Activity Rates

Finally, LDM computes activity rates, according to the methods shown in the following section. Once the activity rates are known, they change the resource quantities according to the following equation:

$$REMAIN_i(P) = AVAIL_i(P) - \sum_j (a_{ij} \times ACT_j(P)) \tag{B.6}$$

where:

$ACT_j(P)$ = rate of activity j during period P.

This brings the calculations full circle; LDM is ready to begin the next simulation cycle.

COMPUTING ACTIVITY RATES

The Computational Cycle

Activities are defined by groups of SUPPORT file records headed by PIPE records. Two data elements in each PIPE record have not yet been discussed: the Blue priority (columns 47–54) and the Red priority (columns 63–70). The following is a sample of SUPPORT records that define activities.

```
123456789_123456789_123456789_123456789_123456789_123456789_123456789_
PIPE     BRIGADE   TANK        READY        0.    -10.   0.    -10.
 FROM    BRIGADE   TANK        WEAPON       1            1.
 COEF    BRIGADE   TANK AMM    WEAPON      52.6         29.2
 COEF    BRIGADE   OTHR AMM    WEAPON      12.0          5.45
 COEF    BRIGADE   WPN CREW    WEAPON       4.0          4.0
PIPE     BRIGADE   APC         READY        0.    -10.   0.    -10.
 FROM    BRIGADE   APC         WEAPON       1.           1.
 FROM    BRIGADE   OTHR AMM    WEAPON      16.8          7.56
 FROM    BRIGADE   WPN CREW    WEAPON       4.           4.
PIPE     BRIGADE   TANK        F-KILL       0.0    0.0   0.0    0.0
 FROM    BRIGADE   TANK        ON HAND      1.0          1.0
 TO      BRIGADE   TANK        NEED EVC     1.0          1.0
PIPE     BRIGADE   APC         F-KILL       0.0    0.0   0.0    0.0
 FROM    BRIGADE   APC         ON HAND      1.0          1.0
 TO      BRIGADE   APC         NEED EVC     1.0          1.0
PIPE     DISCOM    TANK        DS REPR     10.0   1.01  10.0    1.02
 FROM    DISCOM    TANK        DS QUEUE     1.0          1.0
 TO      DISCOM    TANK        ON HAND      1.0          1.0
 COEF    DISCOM    MMH         REPAIR      40.0         40.0
123456789_123456789_123456789_123456789_123456789_123456789_123456789_
```

Among these five example activities, there are negative, zero, and positive priorities. LDM calculates the rates of activities with zero priorities in the combat module, using the CBT_LOSS data from the ATTRITION files (see [3], Chapter 4, and Appendix A of this note). Rates of activities with nonzero priorities (i.e., negative or positive) are calculated in the support module, as described below. Activity rates are calculated in priority order. Thus, the simulation cycle first invokes the support module to compute rates for activities with negative priorities, then it invokes the combat module to compute rates for activities with zero priorities, and finally it invokes the support module a second time to compute rates for activities with positive priorities.

Two of the activities in the example have the same nonzero priority, while one activity has a unique nonzero priority. When two or more activities have the same priority, they share whatever resources they consume in common, rather than one of the activities being able to claim as much of the resources as it can use. The calculation method for activities with shared priorities is more complex than for activities with unique priorities.

LDM computes the activity rates $ACT_j(P)$ according to the following scheme. First, it initializes a vector of resource quantities b_i as:

$$b_i = AVAIL_i(P)$$

For each side (Blue and then Red), LDM loops through all the activities in priority order. When it reaches activity j, it calculates $ACT_j(P)$ in one of four possible ways:

a) If activity j has priority zero, and a CBT_LOSS function corresponds to this activity, LDM calculates $ACT_j(P)$ with that function (see Appendix A).

b) If the priority is zero and there is no corresponding CBT_LOSS function, LDM sets $ACT_j(P)$ to zero.

c) If activity j has a nonzero priority and that priority is unique (not shared with any other activity), LDM calculates $ACT_j(P)$ as described in the following section on "Activities with Unique Nonzero Priorities."

d) If activity j has a nonzero priority and shares it with other activities, LDM simultaneously calculates the rates for all activities with the same priority, according to the method described in the section on "Activities with Shared Nonzero Priorities" later in this appendix.

Following the calculation of activity rates, LDM updates the resource quantities b_i, for each resource i. If, as in the preceding possibilities b) and c), only one activity rate was calculated, say $ACT_j(P)$, b_i is updated according to the equation:

$$b_i = b_i - a_{ij} \times ACT_j(P) \tag{B.7}$$

This updates each resource quantity to reflect the effect that each activity in turn has on it.

If more than one activity rate was calculated (i.e., a group of activities had the same priority), Equation (B.7) is applied repeatedly, for each activity in the group. Referring to Equation (B.6), one can see that once Equation (B.7) has been applied for all the activities, b_i will be left equal to the amount of resource i remaining at the end of the simulation cycle. That is:

$$\mathrm{REMAIN}_i(P) = b_i$$

Activities with Unique Nonzero Priorities

Consider a particular activity j with a unique nonzero priority. If activity j has a positive coefficient in row i of the activity matrix (i.e., if $a_{ij} > 0$), activity j consumes resource i. For example, DS repair of tanks at DISCOM (the activity DISCOM .. TANK .. DS REPR in the preceding example) consumes one tank in the DS queue at DISCOM (the resource DISCOM .. TANK .. DS QUEUE) and 40 maintenance man-hours at DISCOM (the resource DISCOM .. MMH .. REPAIR) for each unit of the activity. Clearly, the rate of this activity cannot be made larger in a time period than the point at which one of these two resources is entirely depleted.

LDM seeks to maximize the rate of activity j; this occurs at the point when the first resource consumed by the activity is depleted. The first resource to be depleted is called the *limiting resource*. In other words:

$$\mathrm{ACT}_j(P) = \mathrm{Min}\ \{b_i / a_{ij} \mid i \text{ such that } a_{ij} > 0\} \qquad (B.8)$$

If $\mathrm{ACT}_j(P)$ is given this value, and the resource quantities are then updated using Equation (B.7), the value of b_i for the limiting resource i will become zero.

The reader may wonder what happens to a resource for which a_{ij} is negative or zero. If the coefficient is zero, nothing happens; resource i is neither consumed nor produced by activity j. If the coefficient is negative, resource i is produced by activity j. When the resource quantities are updated to account for activity j (using Equation (B.7)), one will find that b_i has increased. This raises the possibility that the rate of activity 1, say, will be determined by resource 1; after the resource quantities are updated, b_1 will be zero. Activity 2, whose rate is calculated later, might produce resource 1 (i.e., $a_{12} < 0$). The resource update following the computation of $\mathrm{ACT}_2(P)$ may make b_1 positive, and it might remain so after all the activity rates have been calculated.

The computation cycle can end with resources available to support further increases in some activities. The user can avoid this situation only by cleverly arranging the priority order of the activities.

Activities with Shared Nonzero Priorities

Now consider a group of activities with the same priority. In calculating their rates, LDM first establishes desired proportions among the rates and increases all the rates in those proportions until a resource is depleted. Then it drops any activity from the group that

consumes the depleted resource; the rates of these activities are blocked from further increase. If any activities remain, LDM establishes new proportions for them and increases their rates further, until a new resource is depleted. The process continues until all activities in the group are blocked by a depleted resource.

In establishing these proportions, LDM uses a *principal resource* for each activity. This is the first resource encountered in the SUPPORT file data for which the activity has a positive coefficient in the activity matrix.[5] Let r(j) denote the principal resource for activity j. LDM calculates the rates of activities in the group according to the following algorithm:

0. It initializes the rates of all activities in the group to zero—i.e.:

$$ACT_j(P) = 0, \text{ for all } j \in G.$$

"G" denotes the set of all activities in the equi-priority group.

1. It calculates the desired proportions among the activity rates to be:

$$\Delta_j = \begin{cases} 0 & \text{if for some i, } b_i \le 0 \\ & \text{and } a_{ij} > 0 \\ b_{r(j)} / a_{r(j),j} & \text{otherwise} \end{cases}$$

2. It calculates composite activity coefficients for the entire group of activities, according to the formula:

$$g_i = \sum_{j \in G} (a_{ij} \times \Delta_j)$$

3. It calculates the maximum possible increase in the composite activity:

$$V = \text{Min } \{ b_i \ / \ g_i \mid i \text{ such that } g_i > 0 \}$$

4. It increments each activity rate in the group according to the equation:

$$ACT_j(P) = ACT_j(P) + V \times \Delta_j$$

5. It adjusts the resource quantities to account for these changes in activity rates. In LDM this is done one activity at a time, by repeated applications of Equation (B.7), but it is equivalent to:

$$b_i = b_i - V \times g_i$$

[5] If LDM encounters an activity with no positive coefficient, it terminates with an error message.

When Step 5 is completed, LDM returns to step 1 for another pass. Normally, after one or more passes, it will find all the Δ_j to be zero at step 1, and it will proceed to the remainder of the simulation cycle.[6]

To illustrate this process, consider the two activities with equal priorities in the preceding example. These two activities—namely, BRIGADE .. TANK .. READY and BRIGADE .. APC .. READY—combine resources into tank and APC weapon systems. They both have priorities equal to –10.0, and hence will share their common resources. Their principal resources are those identified in the first FROM line in each activity—namely, BRIGADE .. TANK .. WEAPON and BRIGADE .. APC .. WEAPON, respectively. When applied to this group of two activities, the process just discussed works as follows:

STEP 1: Suppose the available quantities of BRIGADE .. TANK .. WEAPON and BRIGADE .. APC .. WEAPON are 100 and 50, respectively. Then LDM will set $\Delta_{tank} = 100$ and $\Delta_{APC} = 50$.

STEP 2: The composite coefficients (i.e., the g_i) are calculated in the table below. The first two columns are the coefficients of the two activities in the Blue activity matrix. The next two columns are the first two columns multiplied by Δ_{tank} and Δ_{APC}. The last column contains the composite coefficients.

[6]It is possible for LDM to terminate abnormally. This happens only if LDM discovers that some of the activities in the group can be increased without bound (i.e., if all of the composite activity coefficients are zero or negative). Should this happen, LDM will write the following error message:

Log: UNBOUNDED GROUP OF ACTIVITIES
FIRST ACTIVITY IN GROUP IS: (name of activity)

Screen: Execution terminated: UNBOUNDED GROUP

Resource	Act. Coefs BRIGADE TANK READY	BRIGADE APC READY	Col. 1 × 100	Col. 2 × 50	Composite Activity Coefs
TANK	1	—	100	—	100
APC	—	1	—	50	50
TANK AMM	52.6	—	5260	—	5260
OTHR AMM	12	16.8	1200	840	2040
WPN CREW	4	4	400	200	600

STEP 3: LDM compares the totals (last column) against the resources on hand to find the most severely limiting resource. This is done by taking the ratio of the amount of each resource on hand to the total required in the table above, and picking the smallest ratio. For example, assume resources on hand are as shown here:

Resource	Composite Activity Coefs	Total Resources Avail.	Ratio	
TANK	100	100	1.0	
APC	50	50	1.0	
TANK AMM	5260	10000	1.9	
OTHR AMM	2040	10000	4.9	
WPN CREW	600	360	0.6	≤ Limiting Resource

In this example, weapon crew personnel will be the limiting resource.

STEP 4: Increment the two activity rates by 60 percent of their respective Δ_j— i.e., by 60 tanks and 30 APCs, respectively.

STEP 5: Update the resource quantities. The first column in the following table contains the total resources available (taken from the previous table). The second column is the total amount of resources consumed by the two activities, at the rate of 60 tanks and 30 APCs, respectively. The final column is the difference between columns 1 and 2.

Resource	Old Total Resources Avail.	60% of Composite Coefs.	New Total Resources Avail.
TANK	100	60	40
APC	50	30	20
TANK AMM	10000	3156	6844
OTHR AMM	10000	1224	8776
WPN CREW	360	360	0

STEP 1, SECOND PASS: When a second pass is made, LDM discovers that no more WPN CREW are available; because both activities require some WPN CREW, both Δ's will be set to zero. LDM will have completed its calculation of these activity rates, and it will continue with the remainder of the simulation.

But suppose that at step 3 of the first pass, the resources on hand were as follows:

Resource	Composite Activity Coefs	Total Resources Avail.	Ratio	
TANK	100	100	1.0	
APC	50	50	1.0	
TANK AMM	5260	2630	0.5	≤ Limiting Resource
OTHR AMM	2040	10000	4.9	
WPN CREW	600	360	0.6	

From this point, the calculations proceed as follows.

ALTERNATE STEP 4: Increment both activity rates by 50 percent of their Δ_j —i.e., by 50 tanks and 25 APCs, respectively.

ALTERNATE STEP 5: Update the resource quantities. The first column in the following table contains the total resources available (taken from the previous table). The second column is the total amount of resources consumed by the two activities, at the rate of 50 tanks and 25 APCs, respectively. The final column is the difference between columns 1 and 2.

Resource	Old Total Resources Avail.	50% of Composite Coefs.	New Total Resources Avail.
TANK	100	50	50
APC	50	25	25
TANK AMM	2630	2630	0
OTHR AMM	10000	1020	8980
WPN CREW	360	300	60

ALTERNATE STEP 1, SECOND PASS: When a second pass is made, LDM discovers that $\Delta_{tank} = 0$, because the tank activity requires the resource TANK AMM, of which no more is available. However, it will set $\Delta_{APC} = 25$.

ALTERNATE STEPS 2 AND 3, SECOND PASS: The table below shows the new composite activity coefficients g_i, the new total resources available, and the ratio. The new limiting resource is WPN CREW.

Resource	Activity Coefs for BRIGADE APC READY	Composite Activity Coefs. (Col. 1 × 25)	New Total Resources Avail.	Ratio	
TANK	–	–	50	–	
APC	1	25	25	1.0	
TANK AMM	–	–	0	–	
OTHR AMM	16.8	420	8980	21.38	
WPN CREW	4	100	60	0.6	≤ Limiting Resource

ALTERNATE STEPS 4 AND 5, SECOND PASS: LDM now calculates that the APC activity can be increased by another 15 (60 percent of the remaining 25 APCs), and it adds this amount to the previous 25 to make a total activity rate of 40. It updates the resources available, and discovers that the WPN CREW resource is now depleted.

ALTERNATE STEP 1, THIRD PASS: LDM discovers that both Δ_{tank} and Δ_{APC} are zero. LDM continues with the remainder of the simulation, having calculated that in this time step, the activity rate of BRIGADE .. TANK .. READY is 50 and the activity rate of BRIGADE .. APC .. READY is 40.

Appendix C

PARAMETERS, COMMON BLOCKS, AND SUBROUTINES IN LDM

Appendix C presents brief descriptions of the parameters, common blocks, and subroutines in LDM. The parameters and common blocks are declared in the file LDM.INC, while the subroutines are listed in LDM.FOR. Both files can be found on the PROGRAM AND SAMPLE OUTPUT disk on which LDM is distributed (see [3], Chapter 2). The subroutines refer to the LDM.INC as an INCLUDE file, so that when the program is compiled by the RM/FORTRAN compiler, all the lines in LDM.INC are copied into LDM.FOR at each occurrence of the INCLUDE statement.

PARAMETERS

The parameters serve as dimensions for the various arrays used by LDM. A user with a RM/FORTRAN compiler can change the size of LDM by changing the values of these parameters and then recompiling the program. Table C.1 gives the current values and descriptions of the LDM parameters. They are in alphabetical order, which is not the same as the order in which they appear in LDM.INC.

Table C.1

Values and Descriptions of LDM Parameters

Parameter Name	Value	Description
MXACT	500	Maximum number of support activities
MXAME	2500	Maximum nonzero entries in the activity matrix
MXCAS	10	Maximum number of time periods from which output quantities are collected between successive write operations to output files
MXLOS	60	Maximum number of combat loss functions
MXOUT	10	Maximum number of OUT_SPEC files
MXRHS	1200	Maximum number of resource constraints
MXRME	3000	Maximum nonzero entries in the resource matrix
MXTTL	50	Maximum number of title lines in ATTRITION plus SUPPORT files (any number of additional lines are allowed in OUT_SPEC plus TIME_PHASE files)
MXVPO	220	Maximum number of output quantities per OUT_SPEC file
MXWPN	20	Maximum number of weapons per side
NCATS	16	Number of combat worth ratio categories
NPSTR	3	Number of postures (Red Attack, Static, Blue Attack)
NSIDE	2	Number of sides (Blue, Red)

COMMON BLOCKS

The LDM program declares many arrays and scalars in the common blocks found in LDM.INC. They are listed below in alphabetical order, along with (for arrays) their dimensions (expressed in terms of the parameters in Table C.1) and brief descriptions of their purposes.

A1, A2, A3, A4. Temporary storage for numerical inputs or intermediate calculations.

ACNAME(3,MXACT). Activity names, each consisting of three words of eight characters each. Names for activities corresponding to weapons or to CBT_LOSS functions will be encountered first in the ATTRITION file. Names for other activities will be read from the SUPPORT files.

ACTMAT(NSIDE,MXRME). Contains nonzero entries in the activity matrix, in packed form. All elements that correspond to the same activity (i.e., column) are grouped together, with no elements from other activities intervening. For each nonzero entry, the array IACTCN contains the index of the constraint (i.e., row) to which it corresponds. The array IACTBR allows one to determine to which activity each nonzero entry corresponds.

ACTVAL(NSIDE,MXACT). Contains the rates of all activities for each side, in the current simulation cycle.

ATPRM(MXWPN,NSIDE,NPSTR,NCATS). ATTRITION functions, read from the ATTRITION file.

ATTRIT(NSIDE,MXWPN). Number of weapons hit, by side and weapon. This is recalculated in each simulation cycle.

CBTLOS(NSIDE,2,MXWPN,MXLOS). CBT_LOSS coefficients, read from the ATTRITION file.

CNNAME(4,MXRHS). Names of resource constraints. Each consists of three words of eight characters given in the SUPPORT files, plus a fourth word that specifies whether the constraint corresponds to a STOCK or a CONSTR resource.

COEF(MXRHS). Scratch storage, used in SUBROUTINE GROUP while calculating rates of activities with shared priorities.

CONFIL. Name of master control file, entered from the keyboard.

CWCOEF(NSIDE,MXWPN). Combat worth coefficients for the various weapons, read from the ATTRITION file.

CWTOT(NSIDE). Total combat worth engaged on each side, before attrition occurs. This is recalculated in each simulation cycle.

DIST(NSIDE,NPSTR). FLOT movement by side and posture for the current simulation cycle.

DSTPRM(NSIDE,NPSTR,NCATS). MOVEMENT data, read from the ATTRITION file.

E1, E3. Temporary storage for numerical inputs or intermediate calculations.

ENGDST(NSIDE,NPSTR,NCATS). Contains the distribution for the current simulation cycle of Blue and Red combat worths over postures and combat worth ratios (see Appendix A).

ENGRAT(NSIDE). Fraction of available weapons that actually engage in the current simulation cycle. This is read from the TIME_PHASE file.

IACTBR(MXACT+1). In general, for any value of "n," IACTBR(n) equals the index of the first element of the array ACTMAT that corresponds to activity (i.e., column) #n. Because elements belonging to the same activity (i.e., column of the activity matrix) are grouped together in ACTMAT, the indexes of the elements in activity #n are all the indexes between IACTBR(n) and IACTBR(n+1) – 1 (i.e., one less than the first element in activity #n+1). Element NACT+1 contains one more than the index of the last element in ACTMAT.

IACTCN(MXRME). Contains indexes of constraints (i.e., rows) to which the nonzero entries in the activity matrix correspond. The values of those entries can be found in the array ACTMAT.

INFIL. Name of the current input file. This is read anew from each record in the master control file.

INROW(MXRHS). Scratch storage, used in SUBROUTINE GROUP while calculating rates of activities with shared priorities.

IORDER(NSIDE,3,MXACT+1). Information about the priorities of the activities is saved in this array. Thus:

- IORDER(i,1,j) contains the index of the j^{th} activity rate to be calculated for side i.
- The absolute value of IORDER(i,2,j) contains the row index of the first positive element that was encountered while reading the activity matrix data for the j^{th} activity. If IORDER(i,2,j) is negative, the j^{th} activity either has a unique priority or it is the last member of a group of activities that share the same priority. If IORDER(i,2,j) is positive, the j^{th} activity is a member of a group of activities that share the same priority, but it is not the last member.
- If IORDER(1,3,j)= –3, the j^{th} activity had a negative priority, and its rate in any simulation cycle will be calculated before LDM enters the combat module. If IORDER(1,3,j)= –1, the j^{th} activity had a zero priority, but no CBT_LOSS function was found for the activity. Its rate will be set to zero. If

IORDER(1,3,j)=0, the j^{th} activity had a positive priority, and its rate during a simulation cycle will be calculated after LDM returns from the combat module. Finally, if IORDER(1,3,j)>0, the j^{th} activity had a zero priority, and there was a CBT_LOSS function for the activity. Its rate will be calculated using that CBT_LOSS function.

- IORDER(2,3,j) is used for scratch storage.

IOUT(MXOUT,MXVPO). Contains the index numbers of the quantities to be output, from the OUT_SPEC files. This is used along with the information in the TYPOUT array to determine which quantities to collect for the various output files.

IPRT(MXOUT). Array of counters, one for each output file, to determine whether output should be collected in this simulation cycle. This is incremented at each cycle. When an element of this array equals the corresponding element of the NPRT array, output is collected for the appropriate output file and the counter is set to zero. Initially, all counters are set equal to zero.

IRHSBR(MXRHS+1). In general, for any value of "n," IRHSBR(n) equals the index of the first element of the array RHSMAT that corresponds to column #n of the resource matrix. Because elements belonging to the same column are grouped together in RHSMAT, the indexes of the elements in column #n are all the indexes between IRHSBR(n) and IRHSBR(n+1) –1 (i.e., one less than the first element in column #n+1). Element NACT+1 contains one more than the index of the last element in RHSMAT.

IRHSCN(MXRME). Contains indexes of constraints (i.e., rows) to which the nonzero entries in the resource matrix correspond. The values of those entries can be found in the array RHSMAT.

ISTOCK(MXWPN). Contains the activity indexes corresponding to the various weapons.

KEY. Used in several subroutines as temporary storage for an eight-character word from an input record.

KEYWORD. Used in several subroutines as temporary storage for an entire 72-character input record.

LOGFIL. Set to the name of the log file (i.e., REPROL.LOG) in the main routine of the LDM program.

NACT. Number of support activities. This also equals the number of columns in the activity matrix.

NAME, NAME1, NAME2, NAME3. Used in several subroutines as temporary storage for an eight-character word from an input record.

NCASE(MXOUT). Array of counters, one for each output file, to determine how many time periods of output have been collected. A counter is incremented each time output is collected in the OUTPUT array for its corresponding output file. When a counter reaches the value MXCAS (see Table C.1), or when the simulation terminates (whichever occurs first), the accumulated output is written to the corresponding output file, and the counter is reset to zero. Initially, all these counters are set to zero.

NLOS. Number of CBT_LOSS functions.

NOUT(MXOUT). Contains, for each OUT_SPEC file, the number of output quantities requested in that file.

NPRT(MXOUT). Number of simulation cycles per output cycle, for each output file. This is specified by the FREQ_OUT records in either the control file or the individual OUT_SPEC files.

NRHS. Number of constraints, counting both STOCK and CONSTR resources. This also equals the number of rows in the activity matrix, and the number of rows and the number of columns in the resource matrix.

NTIT. Number of title lines collected in the array TITLE.

NTYP. Used as temporary storage for the index of an activity or of a resource constraint while building the activity and resource matrices from data in the SUPPORT files.

NUMOUT. Number of output files defined (one for each OUT_SPEC file).

NVAL. Indicates which half of the RHSVAL array is active during the current simulation cycle.

NWPN. Number of weapons.

OUTFIL. Name of the current output file. This is read anew from each OUT_SPEC record in the master control file.

OUTPUT(MXCAS,MXOUT,MXVPO+2). Temporary storage for values of output quantities between successive write operations to the output files.

POSTUR(NPSTR,NCATS). POSTURE data, read from the ATTRITION file.

RATAVG(NCATS). Records three and four of CATEGORIES data, read from the ATTRITION file.

RATLIM(NCATS). Records one and two of CATEGORIES data, read from the ATTRITION file.

RHSMAT(NSIDE,MXRME). Contains nonzero entries in the resource matrix, in packed form. All elements that correspond to the same column are grouped together, with no

elements from other columns intervening. For each nonzero entry, the array IRHSCN contains the index of the row to which it corresponds. The array IRHSBR allows one to determine which activity each nonzero entry corresponds to.

RHSVAL(2,NSIDE,MXRHS). This array contains the amount of resources available to be used by the various activities. At the start of the simulation cycle, it contains the inherited resources. Then resources are added from outside the simulation (read from the TIME_PHASE file). As each activity rate is calculated, the appropriate adjustments are made to these quantities. See Appendix B for a full description of these calculations. Alternate simulation cycles make use of alternate halves of this array. Thus, in the first cycle, the available resources are in RHSVAL(1,.,.), while in the second cycle, they are in RHSVAL(2,.,.). In the third cycle, they are back in RHSVAL(1,.,.). NVAL indicates which half of RHSVAL is active for the current cycle.

SDEV. Standard deviation of the combat worth ratio distribution for the current simulation cycle. This is read from the TIME_PHASE file.

T1, T3. Temporary storage for numerical inputs or intermediate calculations.

TCYC. Length in hours of a simulation cycle. This is set to 12.0 in the main routine of the LDM program.

TIME. Current simulated time in hours. This is initialized to the first value encountered in the TIME_PHASE file, and thereafter incremented by TCYC at the end of each simulation cycle.

TITLE(MXTTL+1). Title lines from the ATTRITION and SUPPORT files are saved in this array until the output files are defined. When it encounters an OUT_SPEC file, LDM defines an output file and writes all these title lines to it. Title lines in the OUT_SPEC file and in the TIME_PHASE file that follow are encountered after the output file has been defined. They can be written directly to the output file, and hence need not be retained in this array.

TYPOUT(MXOUT,MXVPO). Contains the types of output requested (e.g., INITIAL, REMAIN, ACTIVITY—see [3], Chapter 6) for output quantities specified in the OUT_SPEC files. This is used along with the information in the IOUT array to determine which quantities to collect for the various output files.

VBLOK(MXACT). Scratch storage, used in SUBROUTINE GROUP while calculating rates of activities with shared priorities.

WPNENG(NSIDE,MXWPN). Number of weapons engaged, by side and weapon type, in the current simulation cycle.

SUBROUTINES

The LDM program consists of a main routine plus 32 callable blocks of FORTRAN code. Sometimes a single block will be a subroutine in its own right, and sometimes several blocks will be grouped into a subroutine, with each block having a separate entry point.

The following diagram shows how the various blocks are called. Execution of the LDM program always begins in "Main." The main routine calls CBLSZE, ATTDAT, SPTDAT, and CMPRES, as directed by the records in the master control file. These routines in turn call others, as shown in the diagram. Titles in the diagram show the purposes of major segments of the program.

Main

```
     Read ATTRITION file, and save its data in various arrays
CBLSZE
ATTDAT -+- RDATT   --- ACTLOC
        +- RDCBLS --- ACTLOC

     Read SUPPORT files, build activity and resource matrices
SPTDAT --- RDSPT   -+- ROWLOC --- ROWINS
                    +- ROWINS
                    +- ACTLOC
                    +- ACTINS
                    +- SAFEXP

     Read OUT_SPEC file, and save its data
OUTDAT --- RDOUT

     Prepare for simulation
CMPRES -+- UNBND
        +- SORT
        +- DIMCHK
        +- WRTHED

            Compute available resources (see Chapter 9)
           DTA04   -+- RHSZER
                    +- RHSINH
                    +- RDTIME
                    +- RHDCAL

                       Compute activity rates (see Chapter 9)
                    +- ACTZER
                    +- ACTCAL  -+- ADJRHS
                                +- SINGLE
                                +- GROUP   --- ADJRHS
```

Compute FLOT movement and attrition (see Chapter 8)

```
+- CWCALC
+- ENGTYP
+- HITCAL
```

Collect output quantities

```
+- LDOUT
```

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